

SA21/0th Duty  
NAS8-40000



**Rockwell International**

Rocketdyne Division  
6633 Canoga Avenue  
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RSS-8912

STS-51 PAD ABORT

8-12-93

OV103 - ENGINE 2033 (ME-2)  
FUEL FLOWMETER  
SENSOR OPEN CIRCUIT

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FLOWMETER SENSOR OPEN CIRCUIT  
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STS-51 PAD ABORT  
FINAL REPORT

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## **Section 1.0**

### **Introduction**

## **STS-51 PAD ABORT FINAL REPORT - INTRODUCTION -**

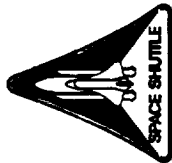
The STS-51 initial launch attempt of Discovery (OV-103) was terminated on KSC launch pad 39B August 12, 1993 at 9:12 AM E.S.T. due to a sensor redundancy failure in the liquid hydrogen system of ME-2 (Engine 2033). The event description and timeline are summarized in Table 1.

Propellant loading was initiated on 12 August, 1993 at 12:00 AM EST. All SSME chill parameters and Launch Commit Criteria (LCC) were nominal. At engine start plus 1.34 seconds a Failure Identification (FID) was posted against Engine 2033 for exceeding the 1800 gpm intra-channel (A1-A2) Fuel Flowrate sensor channel qualification limit. The engine was shut down at 1.50 seconds followed by Engines 2032 and 2030. All shut down sequences were nominal and the mission was safely aborted. Figure 1 depicts the Fuel Flowrate sensor channel disqualification and Figure 2 depicts the abort profile/overlay for all three engines.

SSME Avionics hardware and software performed nominally during the incident. A review of vehicle data table (VDT) data and controller software logic revealed no failure indications other than the single FID 111-101, Fuel Flowrate Intra-Channel Test Channel A disqualification, Figure 3. Software logic was executed according to requirements and there was no anomalous controller software operation, Table 2.

Immediately following the abort, a Rocketdyne/NASA failure investigation team was assembled, (Table 3). The team successfully isolated the failure cause to an open circuit in a Fuel Flowrate Sensor. This type of failure has occurred eight previous times in ground testing. The sensor had performed acceptably on three previous flights of the engine and SSME flight history shows 684 combined fuel flowrate sensor channel flights without failure.

The disqualification of an Engine 2 (SSME No. 2033) Fuel Flowrate sensor channel was a result of an instrumentation failure and not engine performance. All other engine operations were nominal. This disqualification resulted in an engine shutdown and safe sequential shutdown of all three engines prior to ignition of the solid boosters.



# STS-51 ABORT FLOW SENSOR DATA

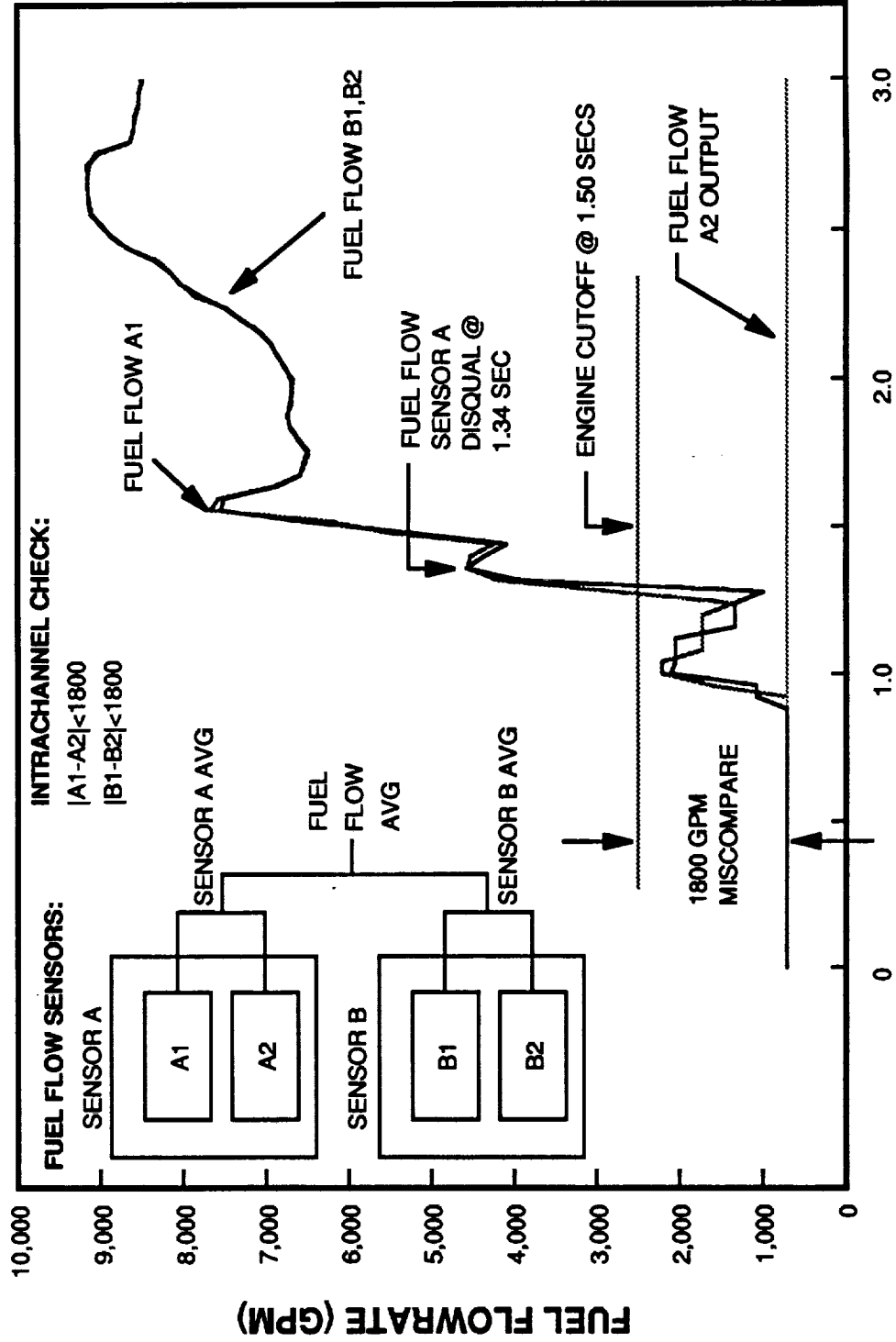
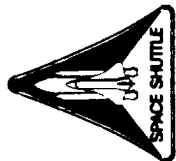


FIGURE 1



# ENGINE PERFORMANCE NOMINAL

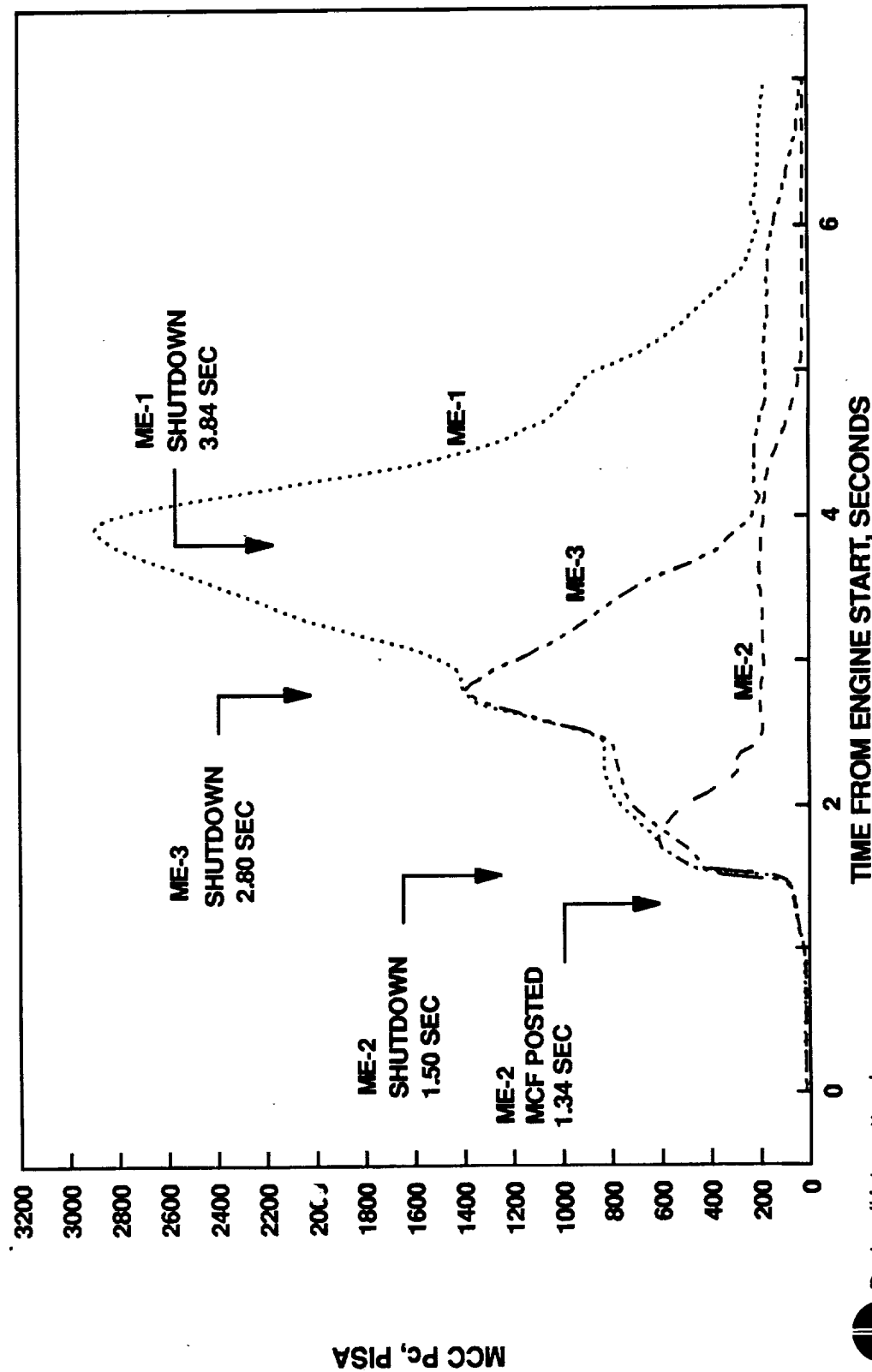


FIGURE 2

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# **DISCOVERY STS-51 ABORT** **FUEL FLOW CH A QUALIFICATION**

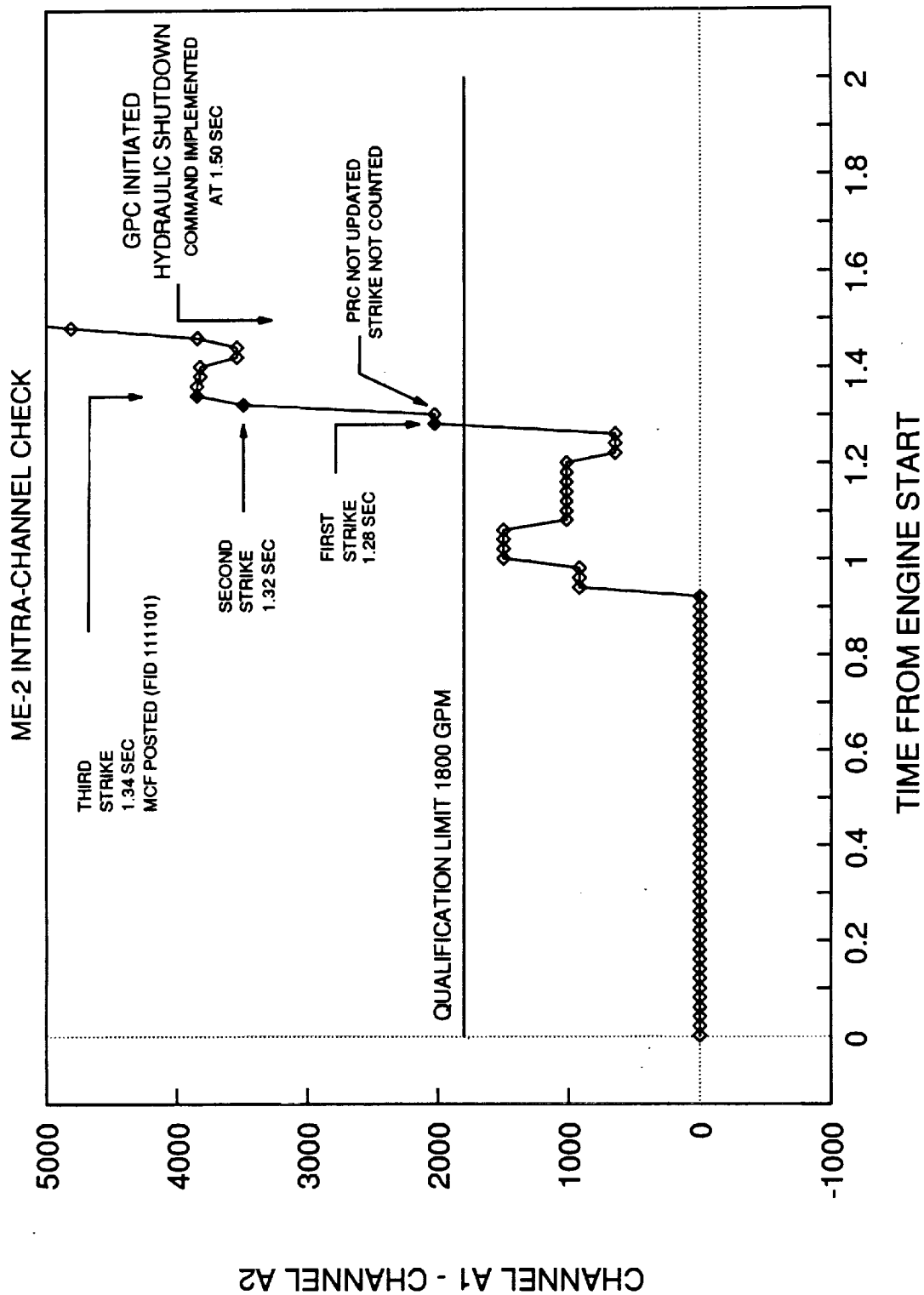
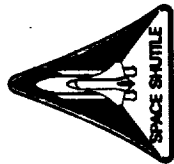


FIG. 3



# DISCOVERY STS-51 ABORT SSME TIMELINE

DAY : HR : MIN : SEC	GMT	EVENT	ME-1 (2030) TIME (SEC)	ME-2 (2033) TIME (SEC)	ME-3 (2032) TIME (SEC)
224 : 13 : 11 : 2.026		ME-1 ENGINE READY	-86.68	---	---
224 : 13 : 11 : 1.496		ME-2 ENGINE READY	---	-87.08	---
224 : 13 : 11 : 1.671		ME-3 ENGINE READY	---	---	-86.84
224 : 13 : 12 : 28.492		ME-3 ENGINE START	---	---	0.00
224 : 13 : 12 : 28.577		ME-2 ENGINE START	---	0.00	---
224 : 13 : 12 : 28.707		ME-1 ENGINE START	0.00	---	---
ME-2 FUEL FLOW CH A INTRA-CHANNEL QUALIFICATION					
224 : 13 : 12 : 29.857		• FIRST STRIKE (  A1-A2  = 2025 GPM )	---	1.28	---
224 : 13 : 12 : 29.897		• SECOND STRIKE (  A1-A2  = 3490 GPM )	---	1.32	---
224 : 13 : 12 : 29.917		• THIRD STRIKE (  A1-A2  = 3845 GPM ) (FID 111101 POSTED)	---	1.34	---
224 : 13 : 12 : 30.077		ME-2 SHUTDOWN	---	1.50	---
224 : 13 : 12 : 31.292		ME-3 SHUTDOWN	---	---	2.80
224 : 13 : 12 : 32.546		ME-1 SHUTDOWN	3.84	---	---
224 : 13 : 12 : 35.092		PREDICTED T-0	6.36	6.48	6.60
224 : 13 : 12 : 46.298		ME-2 POST SHUTDOWN STANDBY	---	17.72	---
224 : 13 : 12 : 47.512		ME-3 POST SHUTDOWN STANDBY	---	---	19.02
224 : 13 : 12 : 48.747		ME-1 POST SHUTDOWN STANDBY	20.04	---	---

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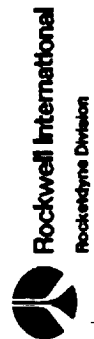
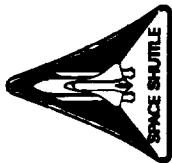


TABLE 1





# DISCOVERY STS-51 ABORT

## ENGINE STATUS WORD

### ME-2 (2033)

GMT HR: MIN: SEC	ENG TIME	SELF-TEST STATUS	MODE	PHASE	LIMIT CONTROL STATUS	FRT STATUS	CHANNEL STATUS	COMMAND STATUS	LOAD MODE
13:08:35.532	-233.05	ENGINE OK	PSN-4	START PREP	ENABLED	NORM OP	OK	ACCEPTED	NO
13:11:01.496	-87.08	ENGINE OK	ENGINE READY	START PREP	ENABLED	NORM OP	OK	ACCEPTED	NO
13:12:28.577	0.00	ENGINE OK	START INITIATION	START	ENABLED	NORM OP	OK	ACCEPTED	NO
13:12:29.917	1.34	MCF	START INITIATION	START	ENABLED	NORM OP	OK	ACCEPTED	NO
13:12:30.077	1.50	MCF	THROTTLE TO 0	SHUTDOWN	ENABLED	NORM OP	OK	ACCEPTED	NO
13:12:35.897	7.32	MCF	PROPELLANT VALVES CLOSED	SHUTDOWN	ENABLED	NORM OP	OK	ACCEPTED	NO
13:12:46.298	17.72	MCF	STANDBY	POST SHUTDOWN	ENABLED	NORM OP	OK	ACCEPTED	NO

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- FAULT TREE
- DATA/TIMELINE
- SENSOR FABRICATION CORRELATIONS

- SENSOR DESIGN/DISASSEMBLY

- AVIONICS
- RELIABILITY/MTBF

- MATERIALS ASSESSMENT

- STRUCTURAL ANALYSIS

- TROUBLE SHOOTING/TURNAROUND REQUIREMENTS
- THERMAL ANALYSIS

- SOFTWARE

- HARDWARE HISTORY

- HAZARD/FMEA CIL
- SAFETY & FINAL REPORT

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## **Section 2.0**

### **Team Recommendations**

## **STS-51 ON-PAD ABORT TEAM FINDINGS & RECOMMENDATIONS**

Tables 1 and 2 summarize key recommendation in response to the investigation findings as related to the sensor. Hotfire testing should be expedited on the current redesigned (new potting material) sensor in parallel to initiating production fabrication for incorporation into the fleet. Close attention to production implementation coupled with successful hotfire test results could support fleet implementation next spring.

Table 3 summarizes key recommendations in response to the investigation findings as related to the software. Table 4 addresses generic issues brought to light during the investigation.

## **STS-51 ABORT TEAM RECOMMENDATIONS - SENSOR**

1. Accumulate minimum five starts on sensors prior to flight use. Limit to twenty-five starts.
2. Test 4 Group (4) sensors for minimum of 25 starts each. Exclude Group (4) sensors from flight until test completion. Acceptable for flight if resulting MTBF is comparable to other groups.
3. Replace all active flight sensors not meeting Items 1 and 2.
4. Re-hotfire screen all NFD sensors meeting Item 1. Use if acceptable for active flight locations. Sensors not meeting Item 1 should be used as NFD sensors for flight.
5. Conduct individual coil resistance check on all flight active coils prior to each flight.
6. Evaluate wire lead bond configuration change to desensitize axial potting crack sensitivity.
7. Destructively disassemble 2 units with more than 80 starts to assess their physical characteristics resisting open failures.
8. Acceptability of sensors for flight should be based upon "sensor failure correlation analysis" ranking of manufacturing and experience factors (Section 7.0).

**TABLE 1**

## STS-51 ABORT TEAM RECOMMENDATIONS - SENSOR REDESIGN

Consider the following redesign options:

1. Increasing the ductility of the potting material so differential strains between the coil bundle and the potting can be absorbed without failure.
2. Reduce the thermal expansion mismatch between the coil and the epoxy layer to reduce the thermal stresses and strains.
3. Coat the wire connecting the coil bundle and the lead wire with a low friction strength coating to promote wire debonding and an increase in the available stretch length of the wire in the event the epoxy layer cracks.
4. Strengthen the outer epoxy layer with high strength fibers (glass fibers, for example) to prevent formation of cracks or, in the event cracks initiate, suppress cracks from achieving sufficient width to cause wire failure.
5. Change the lead wire junction configuration to reduce sensitivity to axial potting cracks intersecting the strain relief wires.
6. Revolutionary approaches to significantly more robust sensor design or flow measurement.

## STS-51 ABORT TEAM RECOMMENDATIONS - SOFTWARE

1. Conduct single coil control hotfire tests to validate software response change to fly with one active coil. (4 coils, min of 2 sensors).
2. Restore MCF & Inhibit response for 1st failure during pre-launch only with LCC monitor active to start enable. Change implemented for STS-62 and subs. Recommend incorporation into first OI-6 delivery.
3. Expedite incorporation of OI-6 software into the flight program.

## STS-51 ABORT TEAM RECOMMENDATIONS - GENERIC

1. Expedite ACTS data update to capture identified missing data in the 1978 to 1981 time frame.
2. Schedule 30% of development hotfire tests to include software redundancy management failure response simulations.
3. Conduct minimum of 2 electrical lockup tests on each of 2 engines. Lockup to be initiated during "Thrust Bucket" transient.
4. Reassess all launch MCF failures comparing sensing system reliability to failure probability (include all failures). Recommend MCF deletions.
5. Re-emphasize need for Block-II E Controller program and Hydraulic Actuator redundancy logic improvement program with focus on significant improvement in PAD abort and erroneous in-flight shutdown susceptibility.
6. Initiate revolutionary design activities directed at order-of-magnitude improvement in critical sensor reliability.
7. Reverse sensor part designation to ensure consistent correlation to LRU codes and ACTS identifiers (See Appendix).

TABLE 4



### **Section 3.0**

#### **Failure Tree Analysis/Failure Scenario**

## **FAILURE TREE ANALYSIS/FAILURE SCENARIO**

### **FAULT TREE**

The fault tree for the STS-51 fuel flow sensor intra-channel check limit violation is shown in Figure 1. The tree is divided into the major branches which distinguish two possible failure modes, 1) a flowmeter mechanical failure preventing required stimulus of the flow sensor and no sensor output, Figure 2, or 2) an electrical failure preventing proper sensor output to the controller or proper output processing by the controller and attendant software, Figure 3.

A third major branch considered was a failure producing fuel flow levels (meter thru flow) below the sensible range of the flow sensor. This was immediately eliminated as a credible failure in-as-much-as all engine and hydrogen pump performance parameters were normal and three of the four flow sensory coil outputs were normal, indicating normal meter thru flow rates.

The tree identifies all components that could have contributed to failure in these major branches and then specific failure modes in each component. Components were eliminated or confirmed as failure candidates by post abort testing, data review, hardware removal with special test and disassembly and system data analysis. Shaded boxes in Figure 1 depict failure modes and failure components not contributing to the flow sensor limit violation. The unshaded boxes in Figure 1 depict the most probable failure path(s) leading to the sensor output violation. The fuel flow sensor coil A lead wire was identified as the failed component via special tests at the supplier and subsequent sensor disassembly observed by the Rocketdyne and NASA failure team personnel (see sections 4.0). The component failure is the probable result of a generic design deficiency in the application thermal environment but may have been influenced by workmanship factors resulting from a five year break in production fabrication of this component.

The following discussion delineates the specific facts and factors leading to the elimination of the shaded boxes in Figure 1.

### **Mechanical Failure**

Mechanical failure would cause erroneous output due to slowing or stoppage of the flow meter rotating parts. This could be caused by contamination, bearing failure, or rotor blade failure.

### **Flow Rotor Failed To Turn or Blade Failure**

The flow meter mechanical system was found to be operating correctly as indicated by three of the four flow sensing coils, Figure 4.

### **Electrical Failure**

Electrical failure divides into three possibilities: Controller, Sensor, or Harness, Figure 3.

No problems were observed during the trouble-shooting with any of the electrical components post abort (PR2033-0142). The controller was used to perform numerous sensor checkouts. These were done while moving the harness and connector. As part of the trouble-shooting the connector at the sensor was removed and the controller correctly identified the sensor was not installed. A different sensor was installed and again the checkouts were normal, and no failure was indicated using a good sensor.

### **Controller**

The controller branch includes software and hardware. Software is the executable program which was loaded into the computer memory. All other controller related functions are considered to be hardware.

The controller and software were found to be operating correctly post abort with no problems identified during any of the checkouts.

### **Software**

The software used in controller U/N F42 (ME-2) was the same as that used for ME-1 & 3 controllers for this flight. The software was verified at the Huntsville Software Lab prior to delivery to Kennedy Space Center and is functionally identical to that used in the other controllers. The data review post abort verified the response to the input data was correct and there were no self checking parity errors indicating memory upsets.

### **Controller Hardware**

This branch includes electronics and wiring. Electronics are the electronic components not including the wiring. Wiring is considered to be the wires connecting

the electronic components within the controller.

The controller was used to do the initial trouble-shooting of the sensor and harness by running sensor checkouts after the abort and operated normally (IPR2033-0142). Although this gave some confidence that the controller was good, the controller was removed and sent to Honeywell for further testing.

### **Controller Electronics & Wiring**

The following tests were conducted at Honeywell to further eliminate controller U/N F42 as a potential cause for the sensor output failure:

- Baseline Functional Testing
  - Continuity check of sensor input circuit
  - Pulse Rate counter check-out
- Environmental testing while performing functional tests
  - Cold start thermal cycle and two high voltage thermal cycles
  - Vibration testing in each of three axis: 10 minutes @ 3.5 Gs, 3 minutes @ 7 Gs, 10 additional minutes @ 3.5 Gs (Total of 69 minutes of vibration testing)
- Acceptance Functional Testing

During all of the testing the controller performed to specification. All testing was performed while monitoring the fuel flow circuits for overvoltage which could damage a flow coil - no anomalies were detected.

The results for these tests are documented in Honeywell Customer Engineering Letter Number 3-SSEC-2332 (see appendix).

### **Controller Induced (Failure Of The Sensor)**

A circuit analysis was conducted to determine if the controller could produce a failure in the sensor. The minimum current required to fuse the sensor coil wire is 500 mAMPS. The worst case direct short to the coil would be a maximum of 80 mAMPS at minimum temperature. This is a short between the Logic Supply Voltage through the Pulse Rate Converter on the 1E3 card to the sensor coil.

The sensor checkout circuit was reviewed and since the sensor A2 coil is isolated electrically from the checkout voltage it was eliminated as a possible cause, Figure 5.

## **Harness**

The connector is considered to be the mechanical source which connects to the adjoining components and the connection wire.

## **Connectors**

The connectors were visually inspected and no evidence of mechanical damage was noted (Figure 6). Once demated no evidence was noted of bent or broken pins. During sensor checkout post abort the connectors were wiggle checked with no problems (IPR2033-0142).

The connectors were disconnected and the standard post installation checkouts (continuity and insulation resistance) were performed with no problems. This testing is documented in KSC TPS 2033-050.

## **Harness Wire**

The wire harness was visually inspected and no evidence of mechanical damage was noted. The harness was wiggle checked during sensor checkout post abort with no problems (IPR2033-0142).

The harness was disconnected and the standard post installation checkouts (continuity and insulation resistance) were performed with no problems. This testing is documented in KSC TPS 2033-050.

## **Sensor**

Failure modes were divided into magnet and wire.

## **Sensor Magnet**

The magnet was eliminated since the A1 coil which is coincident with the failed coil was providing a normal signal. This is documented in the FUEL FLOW A1 & A2 FLT051A1 data plot. Furthermore, subsequent sensor diagnostic and disassembly revealed no magnet anomalies.

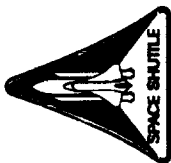
### **Sensor Wire**

During testing at Rosemount the wire in the A2 side of the sensor was verified to make contact at ambient conditions but would be open when chilled. This is consistent with the failure (Figure 7). The final analysis identified that potting compound cracks were the reason for the failure which can be considered a design deficiency. Workmanship problems were also identified which could have contributed to the early failure. This will be documented in Rocketdyne UCR/FAR A032605 and Rosemount disassemble report D9330225.

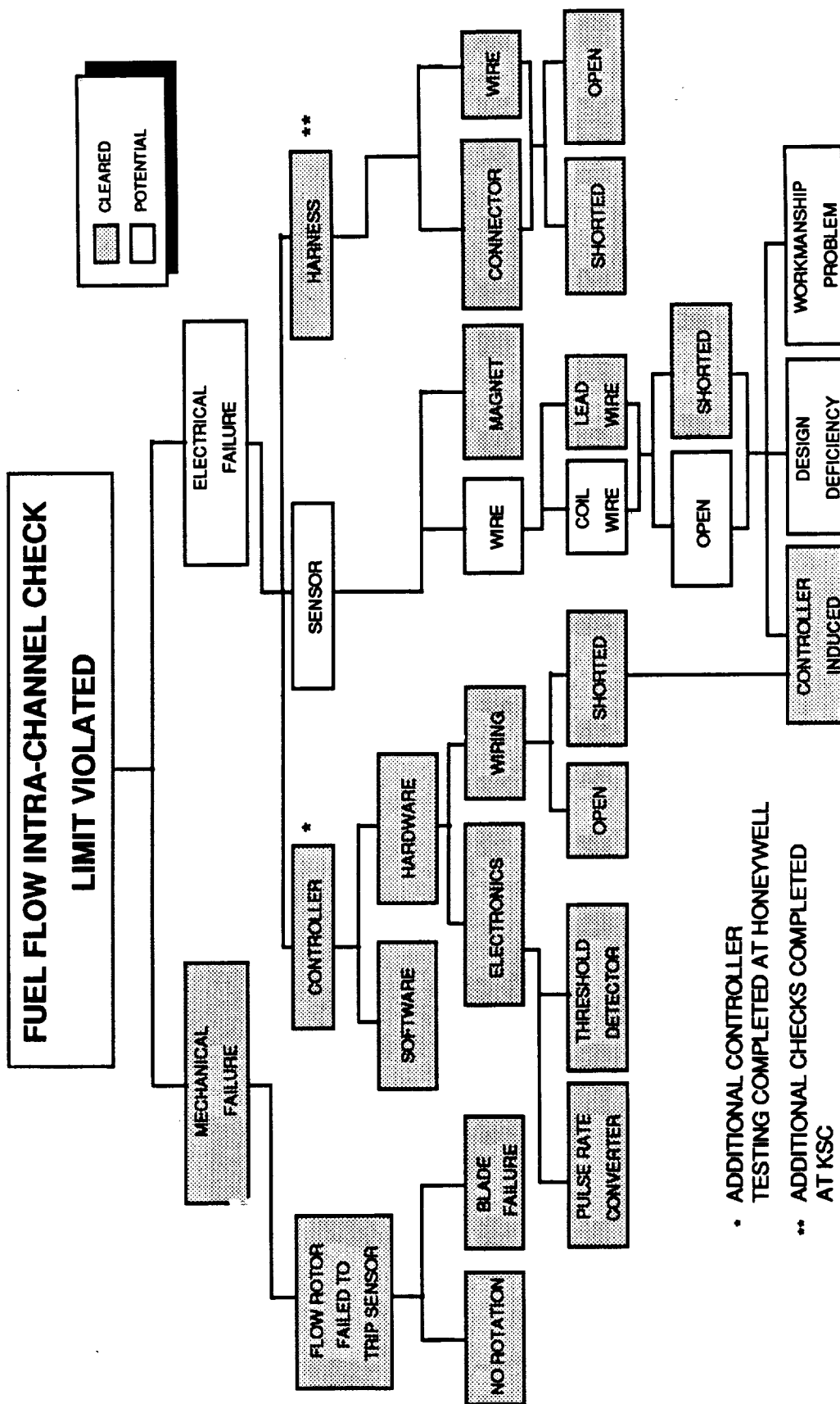
### **Summary**

All possible causes for the fuel flow sensor output disqualification failure have been identified and addressed in the fault tree. The systematic failure investigation results have concluded that an open circuit broken A-2 coil wire resulting in no A-2 coil output at operating conditions was the direct cause of the identified failure.

Based on the evidence completed in the investigation and application of the fault tree logic the most probable failure scenario is summarized in Figure 8.

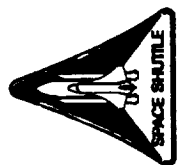


# STS-51 LAUNCH ABORT FAULT TREE



- \* ADDITIONAL CONTROLLER TESTING COMPLETED AT HONEYWELL
- \*\* ADDITIONAL CHECKS COMPLETED AT KSC

FIGURE 1



# FUEL FLOW MEASUREMENT LAYOUT AND PRINCIPAL OF OPERATION

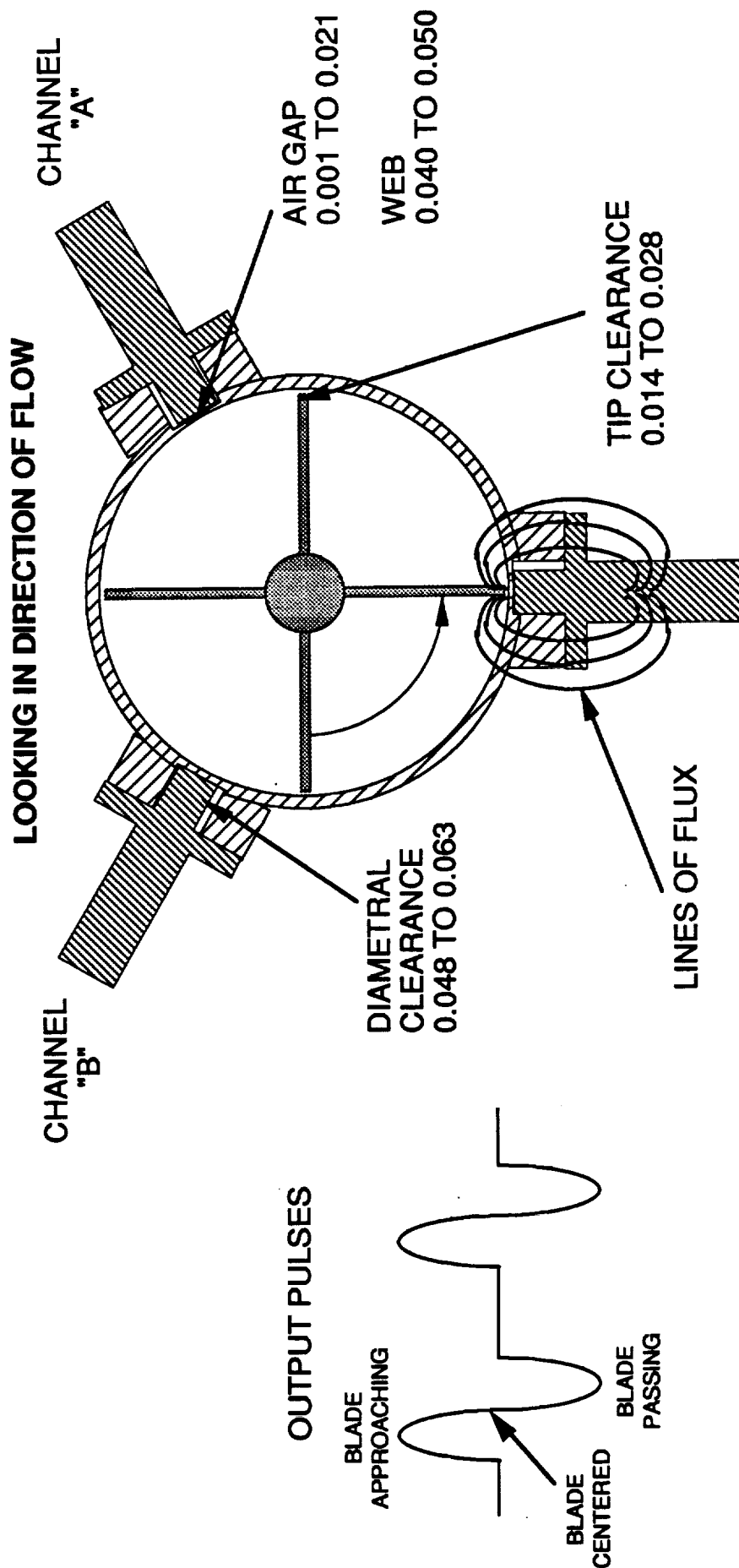
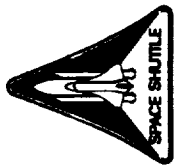


FIGURE 2





# SENSING SYSTEM

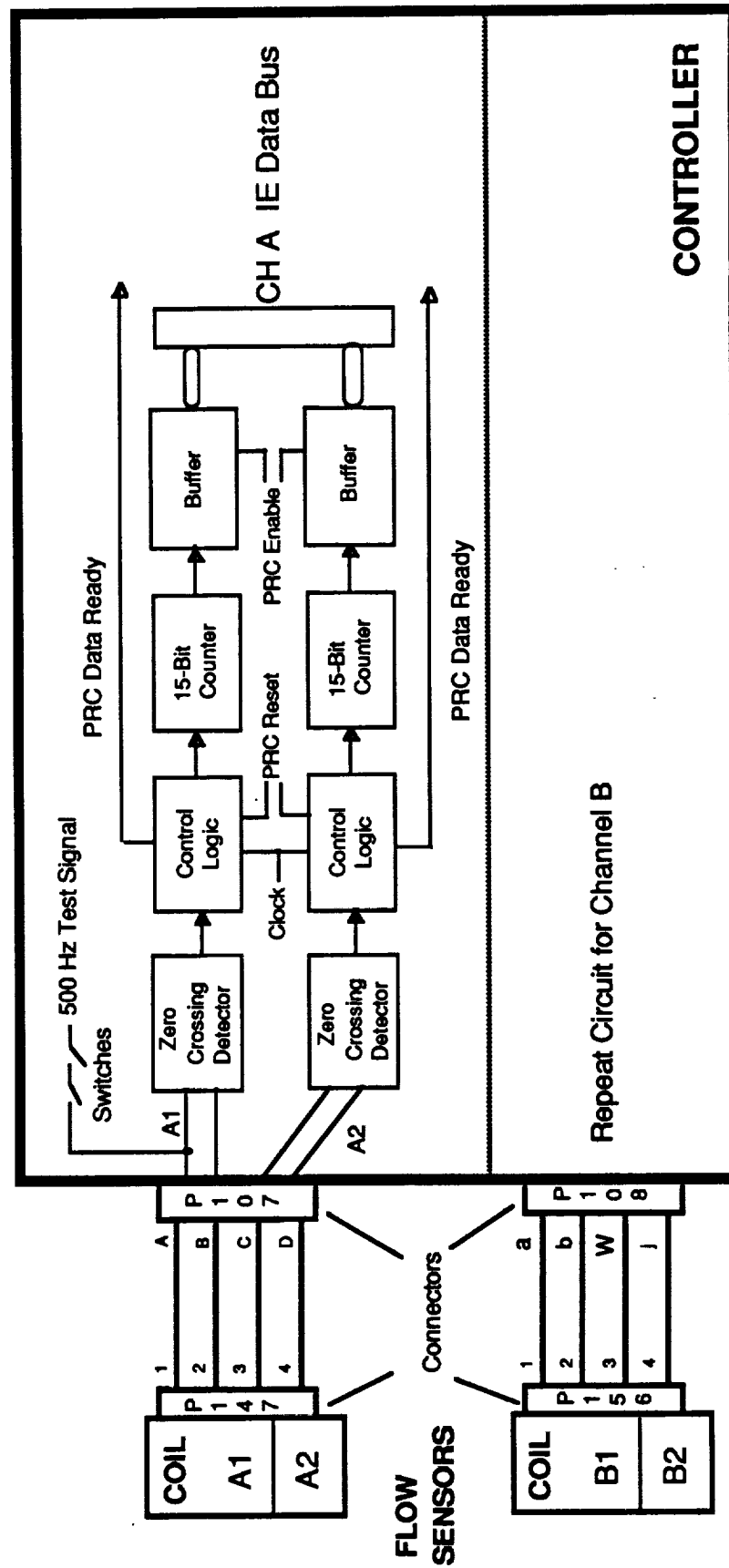
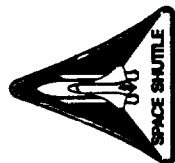


FIGURE 3



# STS-51 ABORT FLOW SENSOR DATA

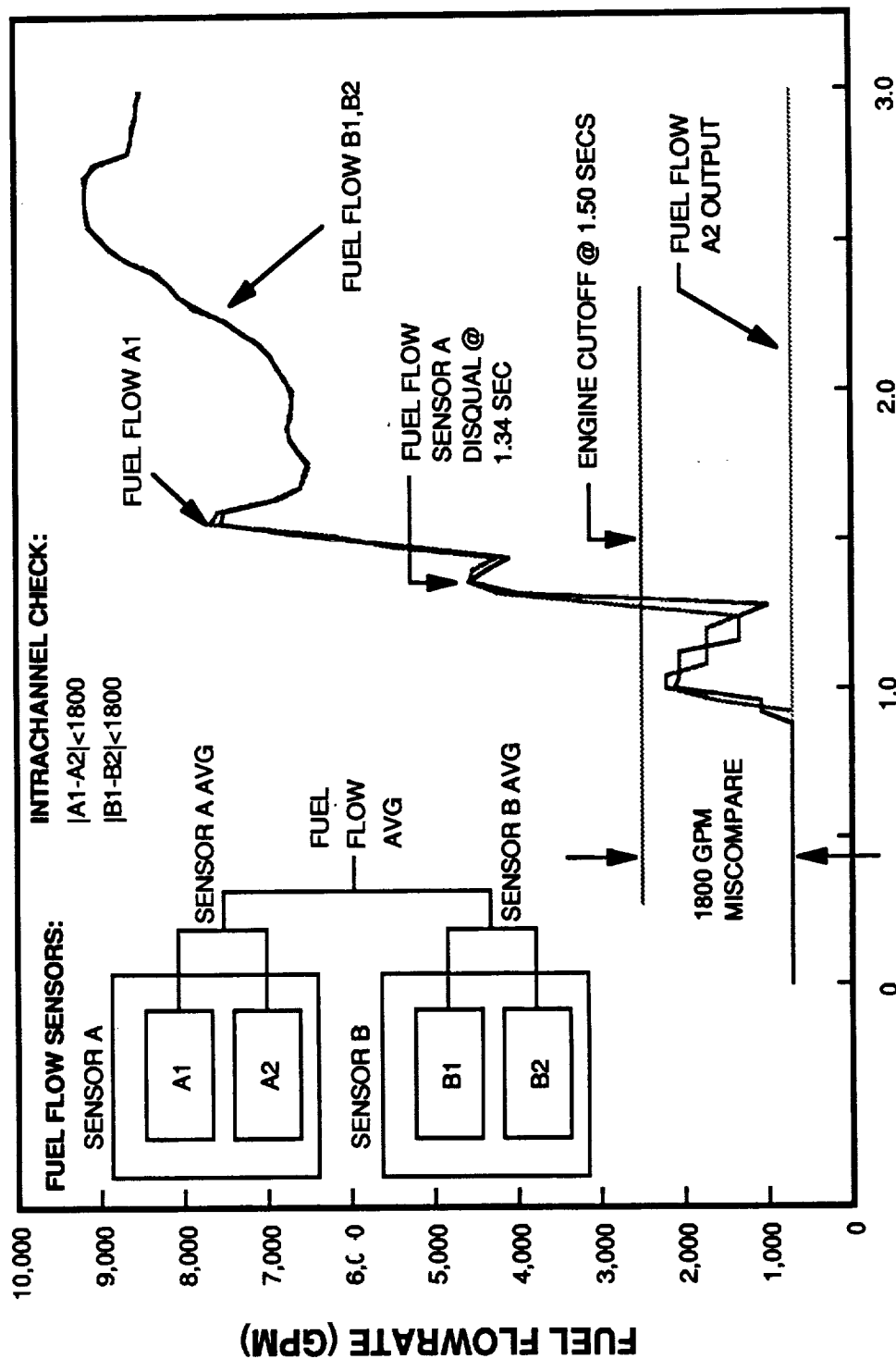
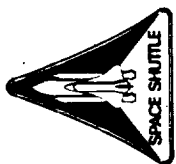


FIGURE 4



# FUEL FLOW SENSOR CHECKOUT

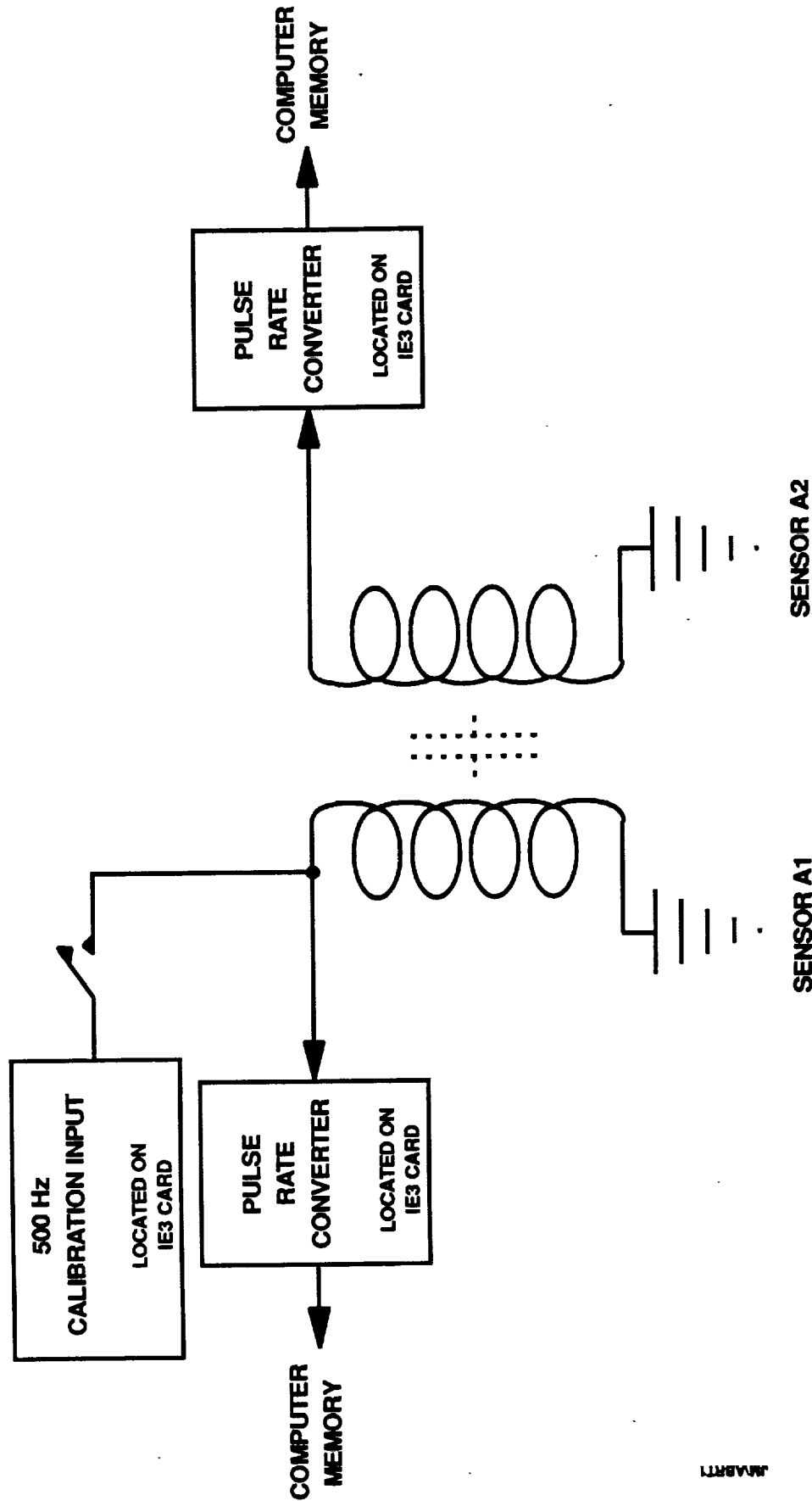
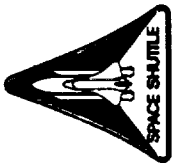
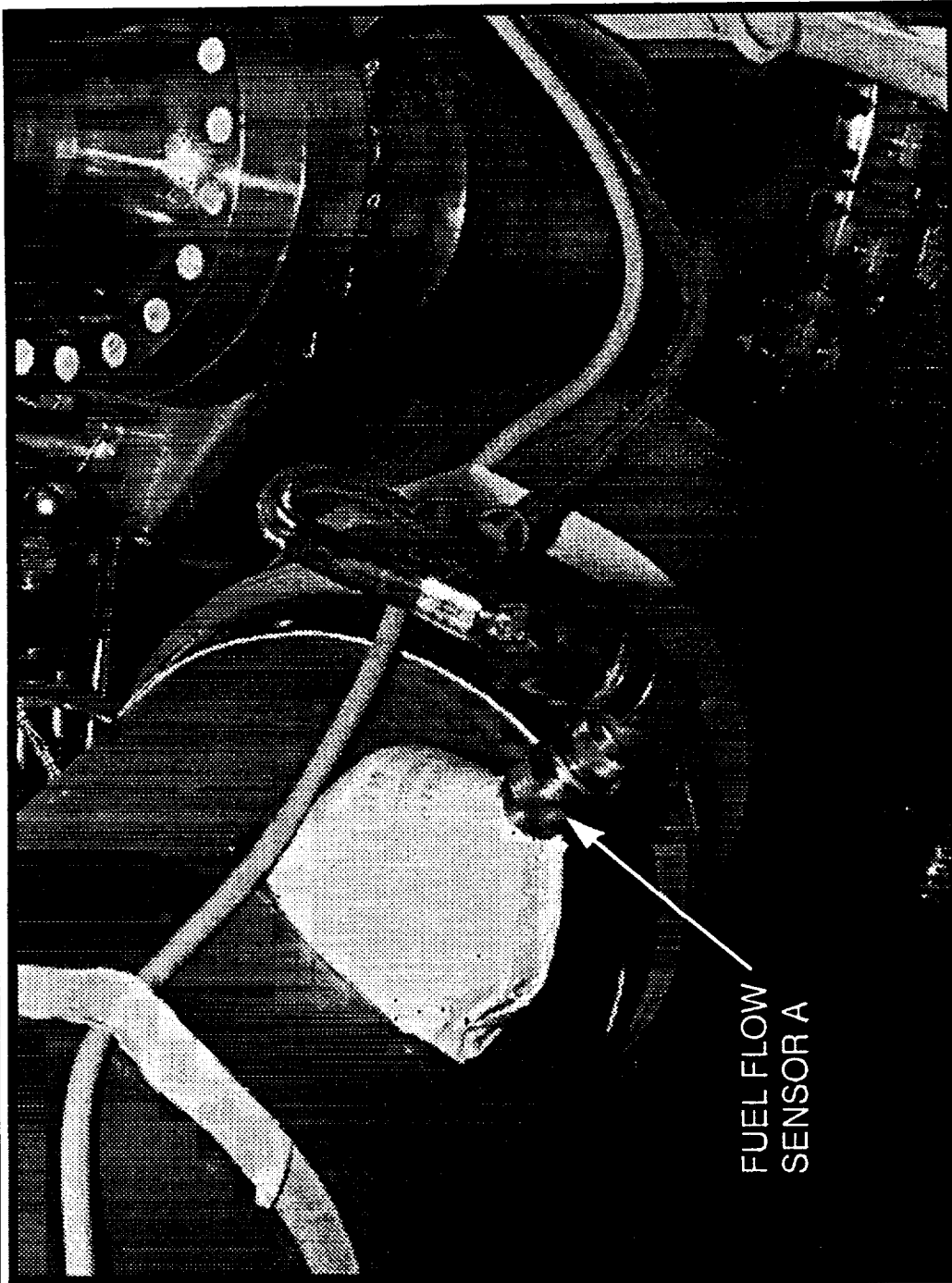


FIGURE 5



# STS-51 PAD ABORT ME-2 (ENGINE 2033) FUEL FLOW SENSOR



V3R151ABRT

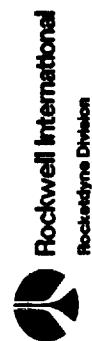
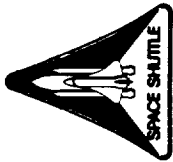


FIGURE 6



# FUEL FLOW SENSOR CHECKOUT

## DETERMINE SENSOR INTEGRITY

### BOTH SENSOR CIRCUITS ON EACH CHANNEL

- INSERT 500 Hz CALIBRATION SIGNAL INTO ONE SENSOR CIRCUIT ON EACH CHANNEL
- PRC UPDATES FOR EACH SENSOR WITH CORRECT VALUE
- NO PRC UPDATES WHEN SIGNAL REMOVED

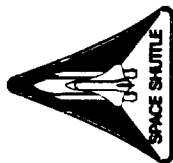
<u>DATE</u>	<u>EVENT</u>	<u>RESULTS</u>
6-27-93	PAD CHECKOUT	NO FAILURES
7-16-93	PRE-LAUNCH SCRUB 1	NO FAILURES
7-23-93	PRE-LAUNCH SCRUB 2	NO FAILURES
8-11-93	PRE-LAUNCH ABORT	NO FAILURES
8-13-93	POST-ABORT	NO FAILURES

	<u>DETECTABLE</u>		<u>COMMENTS</u>
	<u>YES</u>	<u>NO</u>	
• CONTINUITY LOSS ON "HIGH SIDE"	X		
• CONTINUITY LOSS ON "LOW SIDE"		X	MAY OPERATE NORMALLY
• TEMPERATURE DEPENDANT FAILURES		X	



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FIGURE 7



# **STS-51 PAD ABORT (ENGINE 2033)** **FAILURE SCENARIO**

EVENTS	DATA
(1) FUEL FLOW SENSOR POTTING CRACK INITIATED DUE TO CRYO CHILLING	<ul style="list-style-type: none"> <li>• POTTING MATERIAL SUSCEPTABLE TO CRACKING UNDER CRYOGENIC TEMPERATURES</li> <li>• POTTING CRACKING FOUND IN FAILED UNITS</li> </ul>
(2) CRACK GROWTH AFTER REPEATED CRYO CYCLES CAUSED COIL WIRE TO BREAK BUT UNDETECTED DURING SENSOR CHECKOUT (AMBIENT) OR CRYO LOADING	<ul style="list-style-type: none"> <li>• 7 SUCCESSFUL HOT-FIRES INCLUDING 3 FLIGHTS PRIOR TO FAILURE</li> <li>• 3 SENSOR CHECKOUTS @ AMBIENT CONDITIONS PRIOR TO ABORT SHOWED NO ANOMALIES</li> <li>• NO DETECTION METHOD DURING PRELAUNCH CRYO LOADING SEQUENCE</li> <li>• POST ABORT SENSOR CHECKOUT SHOWED NO ANOMALIES (AMBIENT)</li> </ul>
(3) UNDETECTED OPEN COIL WIRE CAUSED MISCOMPARE AND ENGINE SHUTDOWN	<ul style="list-style-type: none"> <li>• FAILURE DUPLICATED AT VENDOR UNDER CRYO CONDITIONS (LN2) - RECOVERY @ 57°F</li> <li>• TEARDOWN INSPECTION INDICATED CRACKED POTTING</li> <li>• CONFIRMED COIL WIRE BREAK IN 2ND STRAIN RELIEF WINDING AT LEAD WIRE- DUCTILE FRACTURE</li> </ul>

ABORT

FIGURE 8

## **Section 4.0**

### **Flow Sensor Failure Analysis**

## TRANSDUCER FAILURE ANALYSIS

### SUPPLIER "AS RECEIVED" INSPECTION

The transducer was hand carried to Rosemount, Inc. in Eagan, MN by Kelly Geroux and Brian Luther of KSC. The failure analysis was directed by Ernesto Acosta (Avionics) and Jeff Fink (ME&T) from Rocketdyne and Wesley Thompson (S&E Instrumentation) and Rob Lamdon (Materials) from NASA MSFC. The hardware evaluation began on 16 August 1993. No abnormalities were noted during the visual inspection of the external surfaces of the part. The probe tip and electrical connector exhibited no evidence of damage.

### ELECTRICAL FUNCTIONAL CHECKS

The initial testing of the unit was restricted to non-environmental conditions so as to minimize the chance of introducing a fault not originally present. The test parameters match those used during the original production acceptance testing (except in the case of x-ray which is not required). The tests included coil impedance (resistance and inductance), output calibration, simulated output, insulation resistance, dielectric withstanding voltage, and isolation resistance. The resulting data was compared with the corresponding original build values. The two coils exhibited similar characteristics. All parameters repeated within normal limits and are tabulated below:

<u>Test</u>	<u>Units</u>	<u>Coil #1</u>			<u>Coil #2</u>		
		<u>Current</u>	<u>Orig. ATP</u>	<u>Δ(%)</u>	<u>Current</u>	<u>Orig. ATP</u>	<u>Δ(%)</u>
Resistance	Ohms	1282.43	1268.73	+1.1	1285.41	1271.41	+1.1
Inductance	Henries	0.169	0.169	0	0.169	0.169	0
Output @100Hz	Volts AC	1.03	0.975	+5.6	1.05	1.00	+5.0
Output @200Hz	Volts AC	2.10	2.08	+1.0	2.15	2.10	+2.4
Output @300Hz	Volts AC	3.20	3.20	0	3.22	3.25	-1.0
Output @400Hz	Volts AC	4.40	4.50	-2.2	4.50	4.55	-1.1
Output @500Hz	Volts AC	5.70	5.60	+1.8	5.80	5.70	+1.8
Simulated output	Volts AC	n/a	n/a	n/a	7.67(1)	3.72	n/a
IR	Megohms	28K	30K	-6.7	28K	30K	-6.7
DWV	Microamps	<100	<100	0	<100	<100	0
Coil Isolation	Megohms	n/a	n/a	n/a	>100	>100	0

(1) Operator error resulted in incorrect frequency (5kHz instead of 500 Hz)



In addition, the part Fig. 1 was subjected to real time micro-focus x-ray examination as a non-destructive technique for assessing evidence of internal anomalies. The 32AWG wires were clearly visible, however, the individual 45AWG coil wires were not apparent. A "spiral like" feature observed on the x-ray image, but within the coil below the potted lead wire area, could not be positively identified as a potting crack or correlated to any coil feature.

## ENVIRONMENTAL TESTING

The next phase of evaluation included those tests from the build and acceptance test procedure with environmental extremes of temperature and vibration. The first indication of a problem surfaced during the "Coil Isolation" test actually performed in the preceding section. After chilling the unit and checking it electrically, the operator swapped test leads and checked for continuity on both coils. Coil #2 was found open, however, it was not known at what point the open actually occurred as the equipment monitors only the coil to coil isolation. The fact that the open circuit was reproduced using the thermal cycle fixture suggested that a temperature chamber might provide greater control over rate, thereby permitting detection of the actual conditions at which the open occurs. During the chamber thermal cycling the continuity of both coils was continuously monitored. Coil #2 opened during the first cycle in LN2 at approximately 25°C (coil resistance measured 1225Ω to 1227Ω).

Stray capacitance measurements were performed on the various connector leads in an attempt to ascertain the location of the probable wire break. The resulting data is tabulated below and the low relative capacitance (0.1nF) points to a open in the vicinity of the pin #3 lead:

<u>Pin Connections</u>	<u>Capacitance Values(nF)</u>	
	<u>Room Temperature</u>	<u>14°C (Coil #2 Open)</u>
1 - 3	22.3	0.1
2 - 3	26.2	0.1
2 - 4	22.4	22.4
1 - 4	26.2	26.2

Confirmation of a fault permitted the deletion of the remainder of the tests, including vibration and extended thermal testing.

## HARDWARE DISASSEMBLY

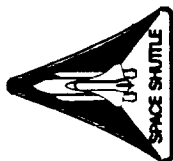
The disassembly of the unit was initiated on the evening of 16 August 1993. First, the probe end cap was machined off. No obvious defects were evident. Next, the sheath

over the coil area was machined partially through its thickness. Finally, the remaining stainless sheath membrane was carefully peeled away revealing the potted coil pickup assembly. A single axial crack was observed in the potting and continuity checks from the electrical connector confirmed that the crack was over the Pin # 3 lead. The appearance of the coil is illustrated in Fig. 2.

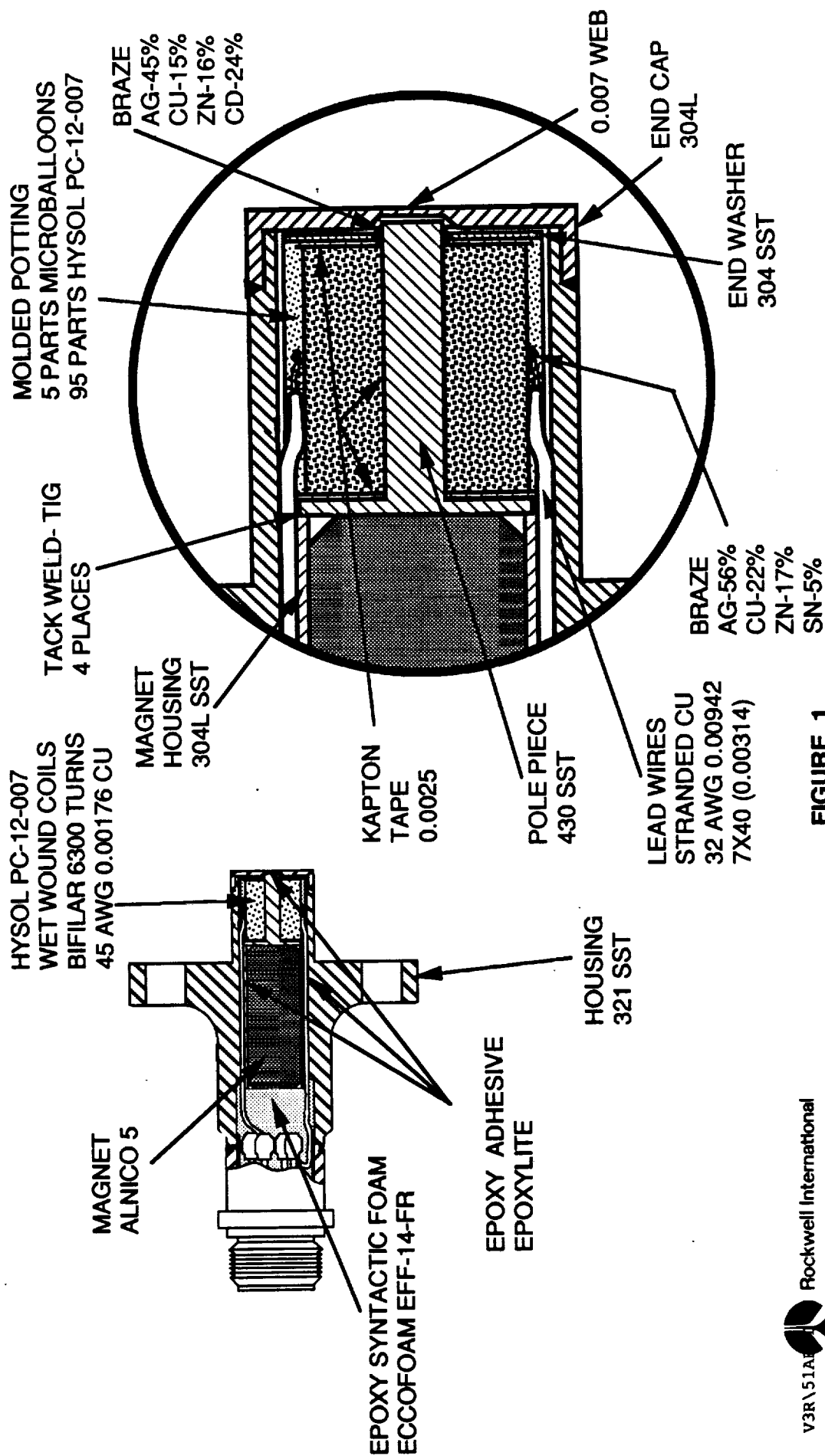
The part was resubmitted for micro-focus x-ray examination, however, removal of the outer 321 stainless steel sheath did not significantly improve the viewing of the coil details. Further visual examination disclosed that the surface crack intersected a void in the potting, where the lead wire teflon insulation erupted through the surface Fig. 3. The surface of the potting was examined with a Scanning Electron Microscope (SEM) prior to being chemically stripping away. The crack appeared widest near the void in the potting and its irregular path followed surface void or non-uniformities.

In addition, it should be noted that the potting appeared to have stratified, in that the microballoon filler was concentrated on the side of the coil away from where the crack was located. Electrical checks confirmed that machining away the sheath caused the intermittent open to become a "hard" open.

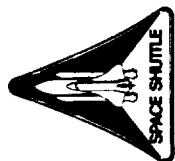
Evaluation of the source of the open condition required that the Hysol PC12-007 potting material be removed in a manner so as to minimize manipulation of the coils and lead wires. Mechanical methods were discounted. A solution of Eccostrip and water was utilized to soften and dissolve the epoxy. Examination of the part after ~2 hours in the solution revealed a suspected break in the coil wire. The part was allowed to remain in the solution overnight. Visual examination resumed on 18 August. Continuity checks through the remainder of the coil verified that the coil itself was intact. Microscopic examination disclosed that the break was located ~375° from braze joint to 32 AWG lead wire (15° into second strain relief turn).



# FUEL FLOW SENSOR CUTAWAY



**FIGURE 1**



## STS-51 FUEL FLOW SENSOR

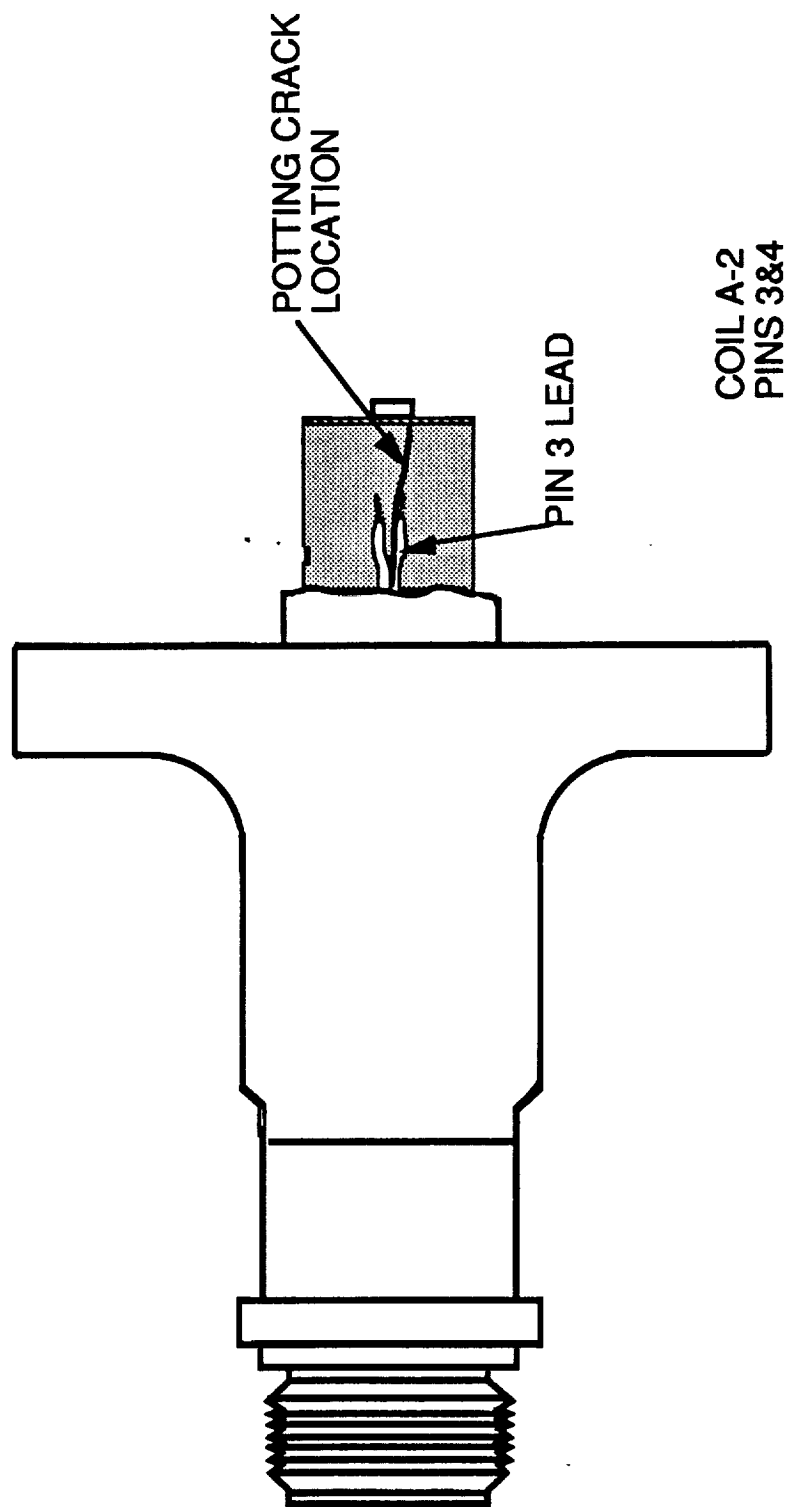


FIGURE 2



# STS-51 FUEL FLOW SENSOR LOCATION OF FAILURE

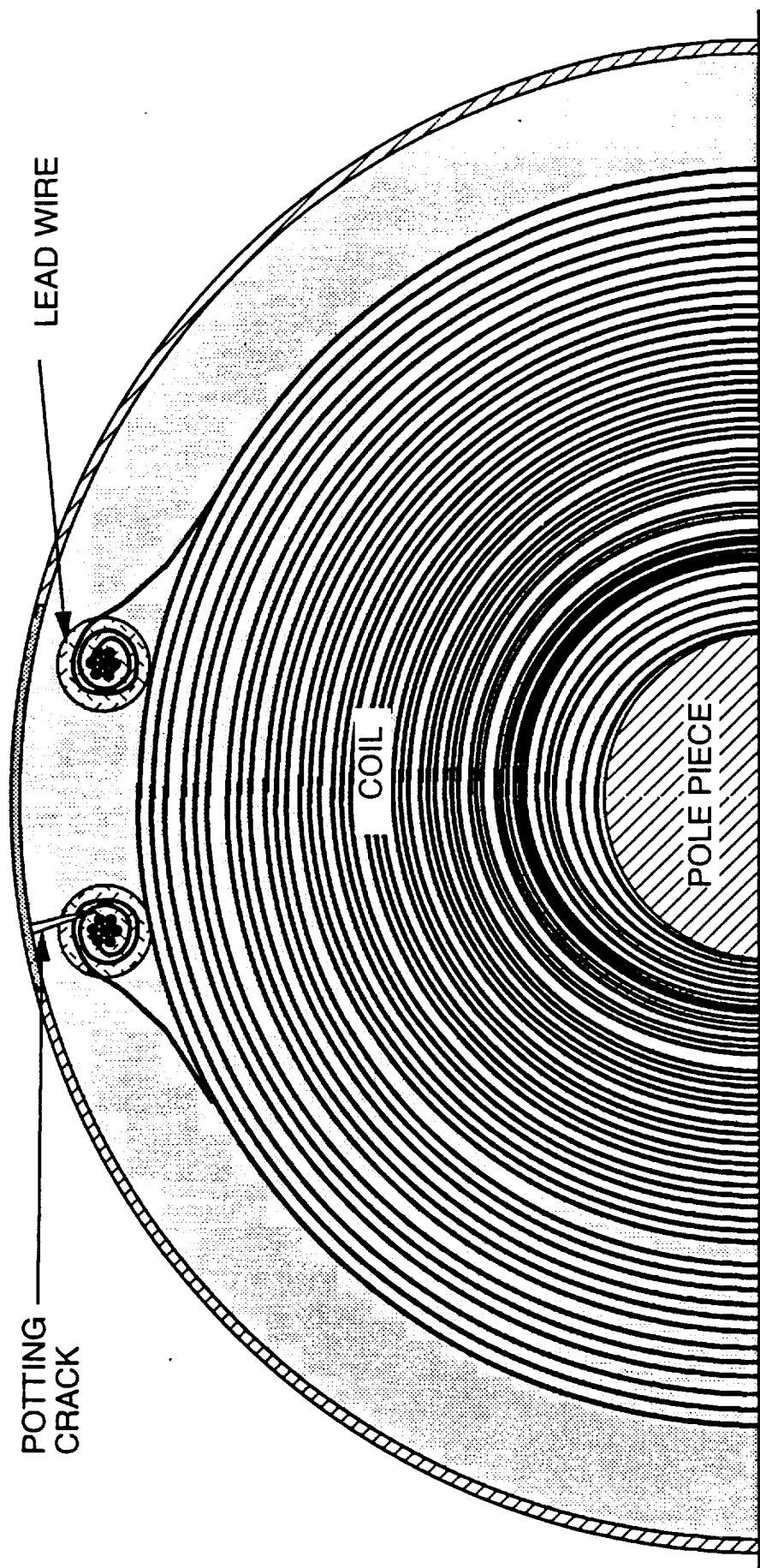


FIGURE 3

## **Section 5.0**

### **Materials Analysis**

## MATERIALS ANALYSIS

### SUMMARY

A systematic examination and tear-down of the RES7005-061, S/N 2582 flow sensor was conducted at Rosemount's facilities in Eagan and Burnsville, Minnesota. Material analysis of the sensor consisted of a preliminary Real-Time X-Ray examination followed by removal of the sensor's end cap and sheath. Detailed visual, Real-Time X-Ray and Scanning Electron Microscope (SEM) examination uncovered an axial crack in the epoxy coil potting. The epoxy was then chemically stripped to reveal a fracture of a coil wire near its braze joint to the pin 3 lead wire. The fracture occurred where the wire spanned the potting crack very near an area of exposed lead wire insulation. Subsequent SEM examinations of both halves of the broken wire suggested the fracture was caused by tensile overload. Two previous cases of failed flow sensors were reexamined and determined to have been caused by tensile overload of coil wires that spanned potting cracks.

### RESULTS

#### Partial Examination

A preliminary Real-Time X-Ray examination of the sensor was conducted prior to disassembly. Views of the coil area through the 321 stainless steel sheath clearly showed the four 32 gage, 0.00942" stranded copper lead wires. However, the 45 gage, 0.00176" solid copper coil wires were not discernible near their braze joints, presumably due to their small size and attenuation of x-rays through the sheath. In addition, no unusual conditions were noted in the connections or wires in the connector end of the sensor.

#### Partial Disassembly

The sensor end cap and sheath were removed by machining to expose the Hysol PC12-007M, glass microballoon filled, epoxy coil potting. An axial crack was evident in the epoxy (Figure 1 & 2) that was primarily collinear with the pin 3 lead wire. The crack was inspected with a binocular microscope and found to extend virtually the entire length of the potting, radiating in both directions from an area of exposed insulation of the lead wire. The crack bottom was not visible. The exposed area of violet-colored Teflon insulation was estimated from photographs to have maximum dimensions of 0.033" by 0.015".

The coil area was reexamined through the epoxy by X-Ray methods. Each coil and lead wire was visible at its braze joint, but no wire fractures or other anomalous

conditions were evident.

The epoxy crack was examined in the SEM and estimated to have a maximum width of 0.002". Although primarily axial, the crack diverted slightly in direction to connect surface imperfections in the epoxy. Neither the braze joint lead wire nor coil wire were visible while viewing down into the interior of the crack. Figure 3 supports the conclusion that the epoxy crack initiated around the perimeter of the island of exposed wire insulation.

### Epoxy Removal

The epoxy potting was soaked overnight in dichloromethane to allow it to soften and slough away. The softened potting was then gently removed and a coil wire fracture was found approximately one and one half stress relief turns from the pin 3 lead wire braze joint (figure 4). A binocular microscope examination of the braze area showed no evidence of joint overheating. The wire fracture was situated directly below where the potting crack had been, in the vicinity of the exposed wire insulation. One end of the fractured wire was still attached to the braze joint, while its mating end was suspended nearby, above the coil windings. The epoxy crack depth appeared to be limited to the microballoon filled potting only and did not penetrate into the general mass of windings. The epoxy was strongly adhered to both halves of the fractured polyamide-insulated wire, making its complete removal difficult. Electrical tests verified this fracture as the only one present in the sensor.

### SEM Examination of Fracture

A detailed SEM examination of the fracture surfaces was attempted, but was made difficult by epoxy residues that deposited on the fracture surfaces during stripping. The fracture surfaces showed a semblance of dimpling which in figure 5 might suggest a tensile overload failure mechanism. Repeated attempts to remove the residue for a clearer examination of the fracture surfaces were unsuccessful.

### Previous Flow Sensor Failures

Two previous flow sensor failures were reexamined at Rocketdyne to determine the failure mode. One (S/N 1969) had a coil wire fracture near the lead to which it was brazed: most failures of the sensor have been reported as similar. Another (S/N 2186) had a fractured coil wire in the general mass of windings, remote from the lead connections. In both cases the fracture was verified by SEM examination as tensile overload and occurred where the wire spanned a crack in the potting.



## FIGURE CAPTIONS

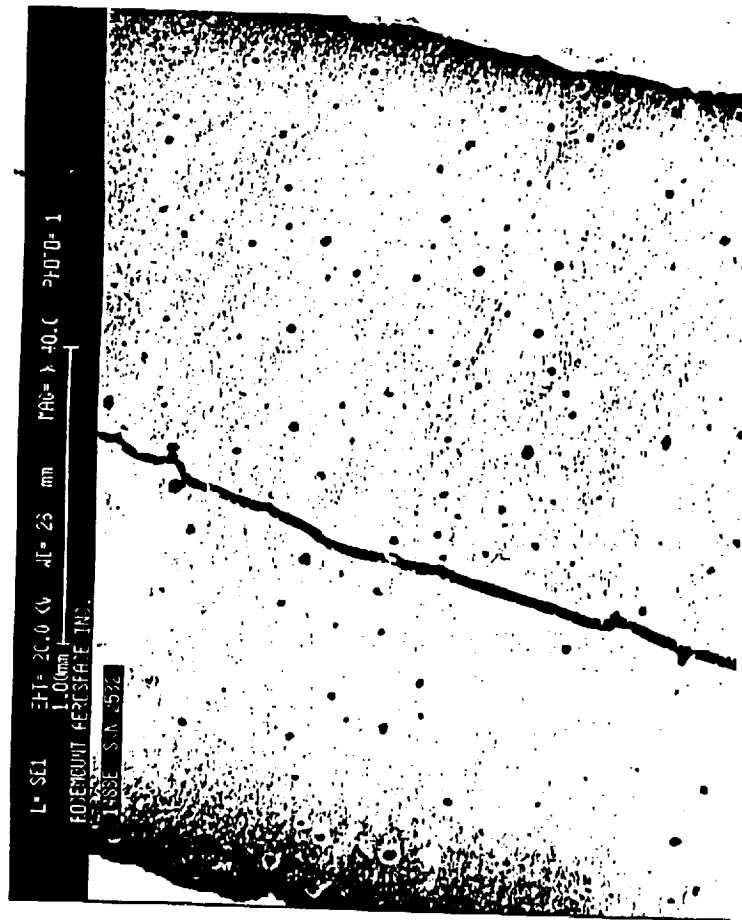
Figure 1. Axial potting surface crack.

Figure 2. Axial potting crack found after sheath removal.

Figure 3. SEM image of exposed pin 3 lead wire insulation and epoxy crack.

Figure 4. Fractured coil wire and pin 3 lead wire after epoxy removal.

Figure 5. SEM image of coil wire fracture.

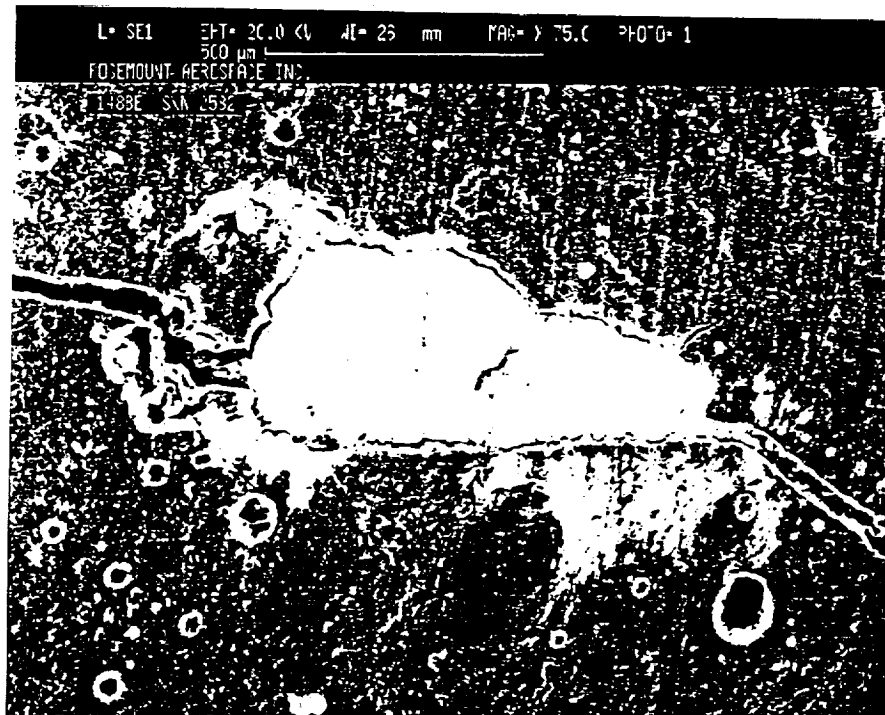


SEM Microphotograph  
of coil potting surface.  
Crack path connects  
voids (40X).

FIGURE 1



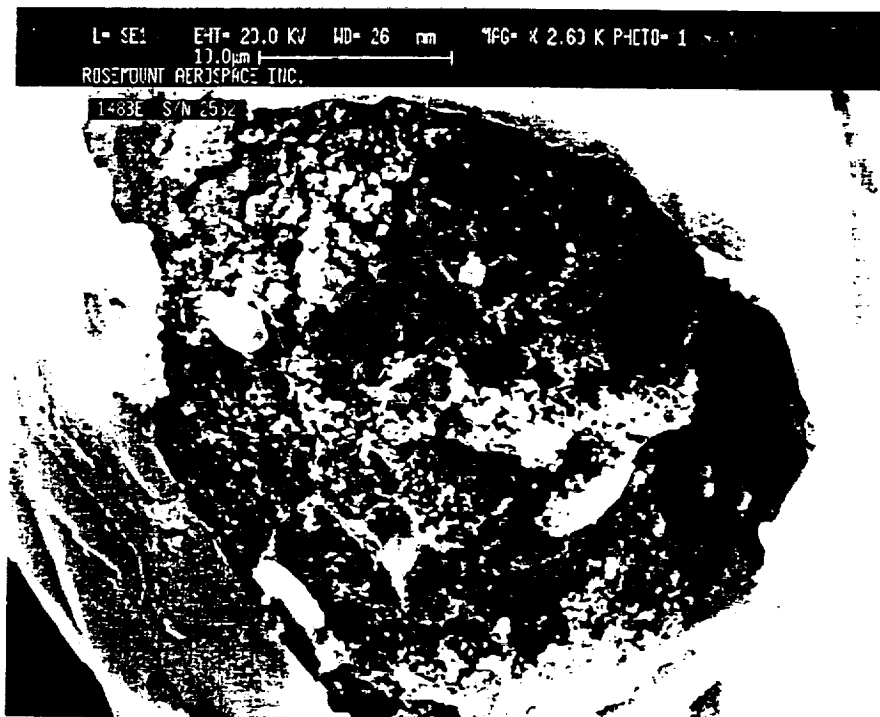
RES7005-61 FLOW SENSOR, S/N 2582 SSME 2033  
EPOXY POTTING CRACK 6X  
FIGURE 2



RES7005-61 FLOW SENSOR, S/N 2582 SSME 2033  
EXPOSED INSULATION & EPOXY CRACK 75X  
FIGURE 3



RES7005-61 FLOW SENSOR, S/N 2582 SSME 2033  
FRACTURED COIL WIRE 25X  
FIGURE 4



RES7005-61 FLOW SENSOR, S/N 2582 SSME 2033  
COIL WIRE FRACTURE SURFACE 2600X  
FIGURE 5

## **Section 6.0**

### **Structural and Thermal Analysis**

## **STRUCTURAL AND THERMAL ANALYSIS**

### **STRUCTURAL ANALYSIS**

Based on the results of the evaluation conducted, the functional failure of the sensor is attributed to the structural failure of the outer sensor potting HYSOL epoxy layer. A thermal stress induced crack in the outer layer of epoxy resulted in severing of the wire embedded in that layer and connecting the sensor coil bundle to the lead wire. The severing of the wire resulted in loss of electrical continuity causing a functional failure of the sensor, Figure 1.

### **DESCRIPTION**

Metallurgical evaluation of the failed sensor unit, subsequent to the aborted flight of STS-51, revealed a crack in the HYSOL epoxy potting surrounding the composite copper/epoxy coil. The epoxy potting contains the 7 strand, 32 AWG lead wire and the 45 AWG wire connecting the lead wire to the coil bundle. The investigation also showed that the 45 AWG wire connecting the coil bundle to the lead wire was severed at the crack plane in the 0.040" thick external layer of epoxy potting.

Based on a comparison of the relative ductilities of the copper wire (approximately 20-30%) and the surrounding HYSOL epoxy (1-3%) it can be concluded, without consideration of any other properties of the two materials, that the only way a copper wire embedded in the epoxy could fail is if the epoxy cracked. Additional conditions for the wire to fail are that the epoxy crack plane crosses the wire and that the wire does not debond from the epoxy as the epoxy cracks. Therefore the analytical effort carried out to determine the cause of failure concentrated on:

- 1) determining if the stresses in the epoxy are sufficient to cause the epoxy to crack,
- 2) determining the width of the crack in the outer epoxy layer and whether the width is sufficient to stretch the wire beyond its ductility limit and
- 3) determining whether the shear bond strength of the epoxy is sufficient to prevent the wire from debonding.

Because of the large differences in the thermal expansion between the wire and the epoxy, thermal stresses were suspected to be the most probable cause of the epoxy crack and the investigation was directed toward quantifying these stresses and determining whether the above three conditions for failure could be satisfied by consideration of thermal stresses alone. Three finite element models were developed to obtain quantitative results needed. The three models, as they relate to the composite construction of the sensor, are schematically illustrated in Figure 2.

The first model (Figure 3) is a three layered, pisegment, shell of revolution, of the pole

piece, the coil and the epoxy potting. The model is based on the assumption of generalized plane strain in the axial direction, requiring only a single layer of elements in the axial direction. It was used to determine the nominal thermal stresses in the epoxy potting at the minimum temperature the sensor is expected to see in service. Only the stresses due to the differences in thermal expansion coefficients were computed. The temperature gradients during the initial cooldown of the sensor were found to be small and were neglected.

The second analytical model developed was a circumferential segment model of the epoxy layer. This model is illustrated in Figure 4 of the Attachment. This model is designed to quantify the amount of "gaping" that would result from stress relief that would occur in the event the potting developed an axial crack.

The third and final model Figure 5 simulates a single strand of 45 AWG copper wire imbedded in a semi-infinite field of epoxy. The purpose of this model is to quantify the shear stress in the bond between the wire and the epoxy as a fraction of the tensile stress of a 45 AWG copper wire imbedded in the epoxy and determine whether the bond between the wire and the epoxy would fail before the tensile strength of the wire was exceeded.

## Results and Discussion

The nominal stresses in the outer epoxy layer were determined using both worst case and best estimate material properties of the copper bundle and the outer composite layer Figure 6. The calculated nominal stresses in the HYSOL epoxy, based on a service temperature of -330 degree F, range between 4600 and 10600 psi (see following thermal analysis). These stresses are equivalent to a tensile mechanical strain between 0.5 and 1.0% and are sufficient to initiate a crack in the epoxy, especially at the outer ligament of the teflon wound lead wire where there is an additional stress/strain concentration. Both ductility data and thermal expansion coefficient data for HYSOL are relatively "soft". However, best estimates of these properties strongly support that the actual strain to ductility ratio is sufficient to cause failure of the epoxy. There is substantial loss of epoxy ductility at cryogenic temperatures and the predicted tensile strains, including the stress concentration caused by the lead wire are in the 1% to 2% range. The most probable failure scenario may be described as follows:

1. the crack initiates in the outer ligament of the lead wire and proceeds more or less parallel to the lead wire,
2. if the 45 AWG wire connecting the core to the lead wire crosses the crack plane and the wire does not debond from the epoxy, the wire fails,

3. if the 45 AWG wire connecting the core to the lead wire does not cross the crack plane or in the event the wire debonds from the epoxy, the wire will survive.

When the epoxy cracks, the wire has a probability of surviving or failing and failure depends on the randomness of the progression of the crack and the details of the core wire / lead wire attachment.

The results of the analysis carried out using the second of the three models shows that, in the event an axial crack develops in the HYSOL outer layer, the crack width at the outside diameter will approach 0.0002". Without wire debond, this crack is certainly sufficient to cause the wire to sever, as this stretch must be absorbed over an infinitesimal length of wire and produces almost infinite local strain.

The results of analysis of the last model show that the wire/epoxy bond shear stresses are approximately 6% of the tensile stresses in the wire. Assuming a 30,000 psi tensile strength in the wire, the maximum shear stresses in the bond will be approximately 1800 psi. Based on the best available data for strength of the HYSOL epoxy, the wire will fail before it debonds. Metallurgical evaluation of the severed wire confirms this conclusion.

Clearly, there is extremely strong evidence that the epoxy will crack, that the wire will not debond and that, in the event the crack plane crosses the wire, the wire will fail.

## **THERMAL ANALYSIS SUMMARY**

It was determined with simplified calculations that the sensor reached virtually steady state temperature within half an hour of the propellant drop, and that there is no significant difference between a 2 hour ground test chilldown and a 9 hour prolonged flight chilldown in terms of the degree of the cooling of the flow sensor. It was also determined that the slow chilldown transient did not generate any significant thermal gradient between the sensor housing and the sensor coil. Both results were later verified with a more detailed 2D model of the sensor, the instrumentation port, and a portion of the duct. This 2D model was also used to quantify additional chilling of the sensor due to engine mainstage operation.

### **Sensor Chilldown Simplified Calculations**

The nomenclature used in the discussion is shown on the cross-sectional diagram of the sensor and the duct port in Figure 7.

A series of single node lumped capacitance calculations were carried out. It was



recognized that the heat transfer is driven primarily by the boiling hydrogen in the duct, and that there is comparatively little effect from the ambient environment since both the sensor and the sensor port are insulated with rigid polyurethane foam. Therefore, the simplest and quickest approach was to calculate the port chilling due to the boiling hydrogen first, and then use the result from it to calculate the sensor flange and housing chilling, and the result from this second step to drive the sensor coil chilling.

The cooldown of the sensor port metal mass was calculated by using an average boiling hydrogen film coefficient of  $20 \text{ Btus/hr-ft}^2\text{-}^\circ\text{R}$  from Seader et. al.<sup>[1]</sup>, and a constant fluid temperature of  $40^\circ\text{R}$ . An equivalent conductance of  $0.32 \text{ Btu/hr-ft}^2\text{-}^\circ\text{R}$  was used for the polyurethane insulation in series with the free convection heating from the ambient or engine compartment environment, assumed to be at a steady temperature of  $460^\circ\text{R}$ . The lumped capacitance approach is justified by a Biot number of 0.15 based on the boiling heat transfer film coefficient and a volume to surface area ratio of 0.6 inch.

Starting from an initial temperature of  $530^\circ\text{R}$ , the port approaches a chilled steady-state temperature of  $59^\circ\text{R}$ , with a temperature of  $60.8^\circ\text{R}$  achieved after only half an hour of chill. A temperature versus time plot for the port is shown in Figure 7<sup>[2]</sup>, together with the sensor coil and housing which is discussed below.

The cooling of the sensor flange and housing was done in the second step, using the calculated duct port transient temperature as the driver. The conductance across the air gaps around the sensor tip was compared with the conduction through the thickness of the sensor housing, and it was found that the latter was an order of magnitude greater than the former. Most significant was the effective contact conductance assumed between the port and sensor flanges, (Figure 7), which was studied parametrically. Later, it became evident that a contact conductance value of  $1500 \text{ Btus/hr-ft}^2\text{-}^\circ\text{R}$  is believed to be more reasonable, it can be concluded from Figure 8 that the flow sensor takes only slightly over half an hour of chill to reach steady state.

The calculated sensor housing temperature was then used to drive the sensor coil. As anticipated, the analysis showed that the temperature difference developed between the housing and the coil is not significant due to the slow transient (Figures 8 and 9). This suggests that the  $\Delta T$  that is pertinent to the cracking of the molded potting between the housing and coil is the overall slow change of the temperature with time, and not the small gradients that develop between the sensor components during the cooldown.

## **2d Thermal Model**

One assumption that was necessary in the simplified calculation described above was to ignore the conduction from the sensor flange in the first step of calculating the duct port chilldown. In the 2D model, the thermal contact between the sensor flange and the port flange was properly accounted for, and its effect on the steady state temperatures of the sensor tip and duct port was determined. In addition, a more detailed temperature distribution was generated for the entire sensor. The 2D mesh is shown in Figure 9 with descriptions of the boundary conditions. Since the flanges of the sensor and the duct port are not fully solid in the circumferential direction, solidities of 0.22 and 0.59 were applied to the elements of these respective components.

The baseline steady state result after a 2-hour chilldown is shown in the contour plot in Figure 11. As mentioned earlier, a constant contact conductance of 1500 Btus/hr-ft<sup>2</sup>-°R was used for the baseline case. There is a large temperature gradient that occurs across the polyurethane insulation as expected, and a small axial gradient from the connector end of the sensor to the tip where the coil is located. The large  $\Delta T$  across the insulation is consistent with almost no radial gradient across the sensor tip (coil, potting, and housing), and the duct port.

Plots of nodal temperatures versus time for the baseline case are shown in Figure 12 for nodes located radially across the sensor tip and the duct port. The effect of having the thermal contact between the sensor flange and the duct port throughout the chilldown in the 2D model is obvious from this figure. With the heat transfer from the sensor to the port properly accounted for in the 2D model, the duct port is predicted to reach a higher steady state temperature of 85°R, compared to 59°R from the simplified calculation, and the sensor steady state temperature is predicted to be lower at 106°R, compared to the worst case 140°R predicted from the simplified calculation.

## **Sensor Chilling During Mainstage Operation**

The 2D model baseline case chilldown analysis was continued for 600 seconds of 104% RPL engine mainstage operation. The forced convection boundary condition in the duct was changed from the boiling hydrogen film coefficient of 20 Btus/hr-ft<sup>2</sup>-°R during chilldown, to 4800 Btus/hr-ft<sup>2</sup>-°R during mainstage. In addition, a heat generation rate of 0.073 Btu/hr was added at the coils, to represent the ohmic heat loss generated by the flow sensor signal at mainstage.

The heat generation rate of 0.073 Btu/hr is too small to have any significance, and the sensor coil chills further during mainstage. As shown in Figure 13, the port cools down further from 85°R to 56°R, and the sensor also cools down further by 26°R, from 106°R to 80°R during mainstage. Overall, this means a sensor tip cooling of 530°R-80°R= 450°R, from the start of chilldown to engine cutoff. This overall  $\Delta T$  based on

estimate of  $530^{\circ}\text{R} - 140^{\circ}\text{R} = 390^{\circ}\text{R}$  from the simplified calculation. However, since the structural analysis ongoing at the time indicated that a  $\Delta T = 300^{\circ}\text{R}$  was sufficient to cause cracking of the molded potting<sup>[4]</sup>, the thermal refinements achieved with the 2D model does not change the conclusion in relation to the cause of the sensor failure.

## REFERENCES

1. J. D. Seader et. al., "Boiling Heat Transfer for Cryogenics", NASA contractor report CR-243, June 1965.
2. R. Principe, "STS-51 HPFP Inlet Fuel Flow Sensor Anomaly Chilldown Temperature Equilibration Analysis", briefing changes BC-93-129-012, 8-16-93.
3. General Electric Company Heat Transfer Data Book, Section 502.5, p. 5, November 1970.
4. Verbal communications with W. Veljovich, D/545-128, on the structural analysis of the flow sensor failure.

## FAILURE MECHANISM

- THERMAL EXPANSION COEFFICIENT MISMATCH BETWEEN THE WINDING COMPOSITE AND THE OUTER POTTING LAYER PRODUCES HIGH TENSILE STRESSES IN THE POTTING
- STRESS CONCENTRATION AT THE INSULATED LEAD WIRE IN THE POTTING MATERIAL INCREASES STRESS CAUSING FAILURE IN THE OUTBOARD LIGAMENT
- CRACK EXTENDS OR PROGRESSES CYCLICALLY ALONG THE WIRE
- IF THE CRACK INTERSECTS THE COIL WIRE, WIRE DOES NOT HAVE SUFFICIENT STRENGTH TO PREVENT POTTING MATERIAL SEPARATION
  - IF THE WIRE DOES NOT DEBOND (HIGH SHEAR STRENGTH BETWEEN WIRE AND EPOXY), IT SEVERS
  - BOTH ANALYSIS AND HARDWARE SHOW GOOD BOND

FIGURE 1

# FUEL FLOW SENSOR FAILURE MODELS

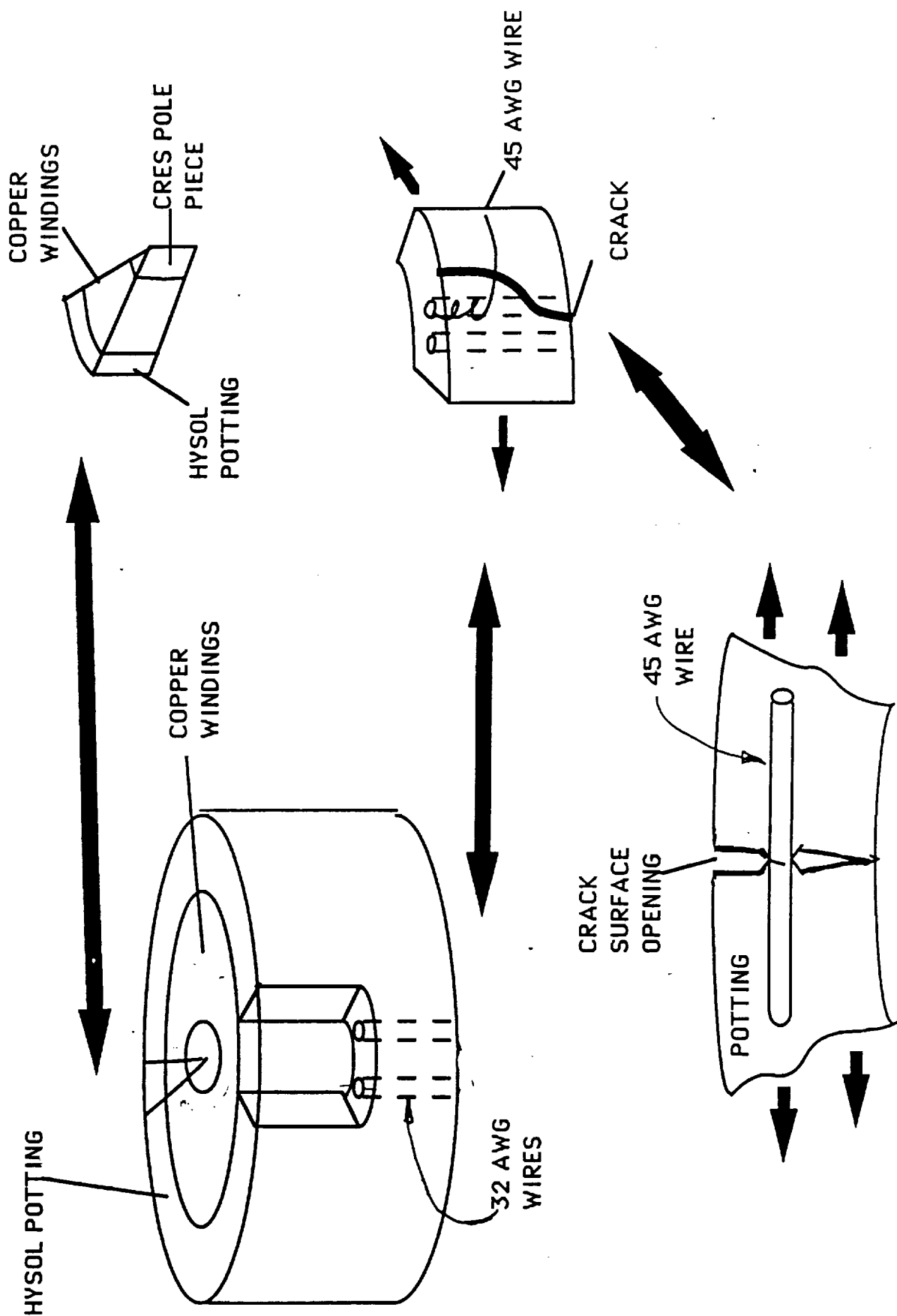


FIGURE 2

# SSHE FUEL FLOW SENSOR WINDING BULK THERMAL STRESSES

08/19/93

IMIN= 0.00E+0  
 IMAI= 0.60E-1  
 YMIN= 1.00E-2  
 YMAI= 0.23E+0  
 IMIN= 0.00E+0  
 IMAI= 0.12E-1

IVAI= 2  
 DD1 = -0.58  
 DDY = 0.58  
 DDZ = 0.58

STRESS<sub>TA</sub>

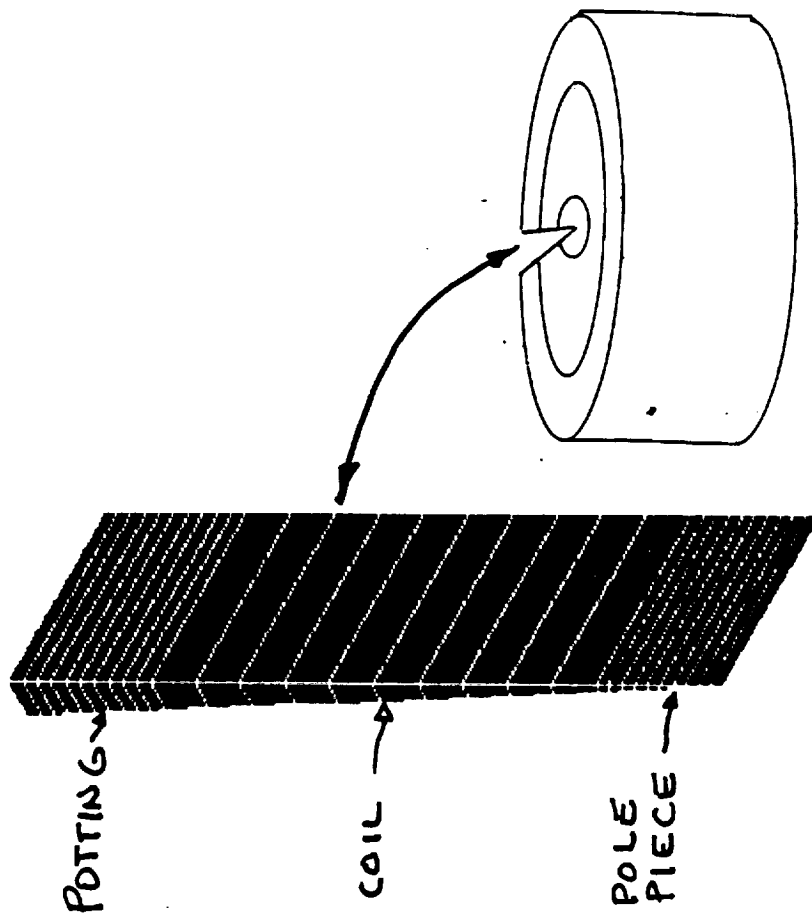


FIGURE 3

# SCHE FUEL FLON SENSOR EPOXY LAYER CRACK GAPPING MODEL

08/19/93

IMIN= 0.00E+0  
 IMAX= 0.30E-1  
 YMIN= 0.95E-1  
 YMAX= 0.24E+0  
 ZMIN= 0.00E+0  
 ZMAX= 0.21E+0

IVAX= 2  
 DDY = -0.58  
 DDY = 0.58  
 DDZ = 0.58

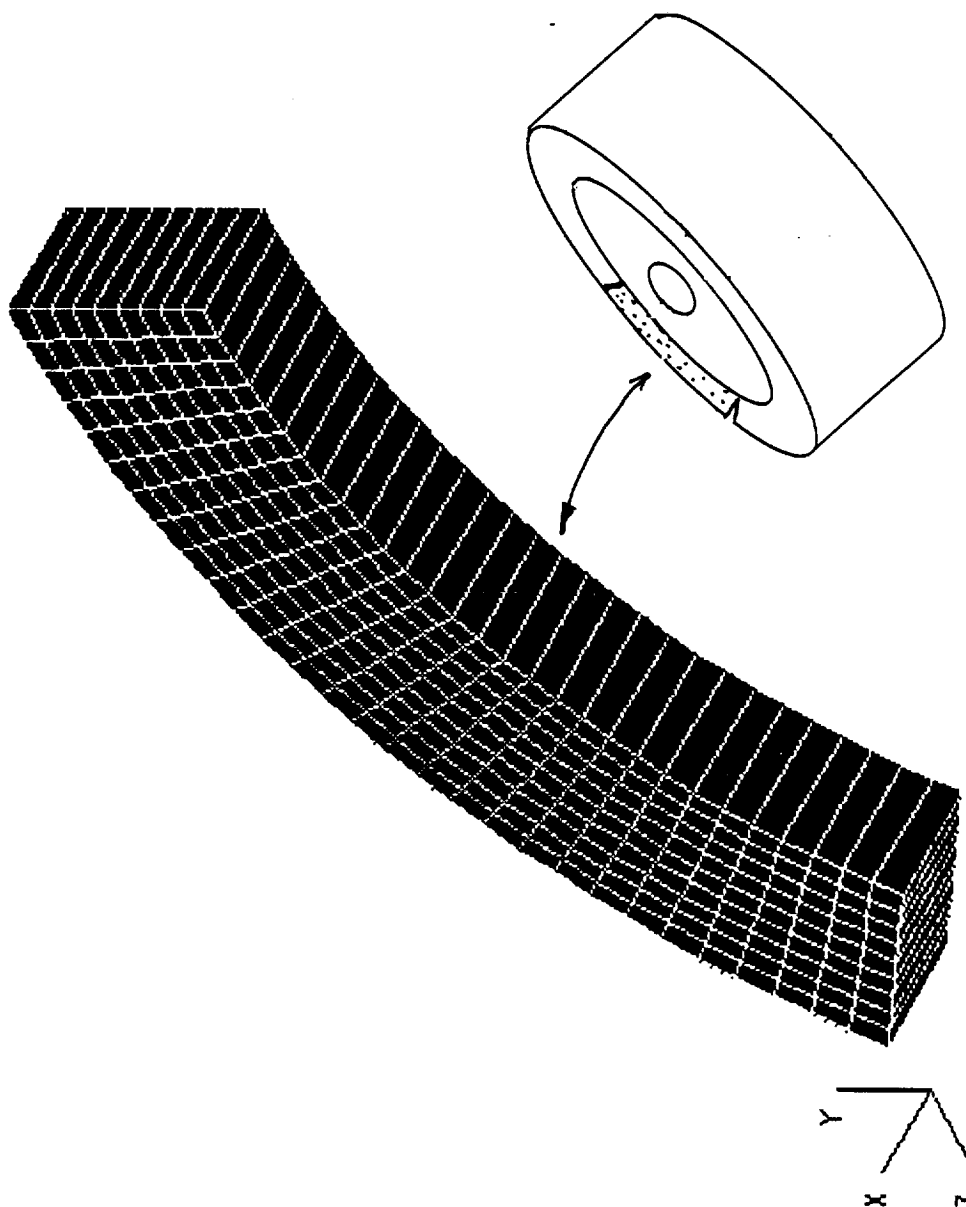


FIGURE 4



# SOME FUEL FLOW SENSOR WIRE PULL-OUT MODEL

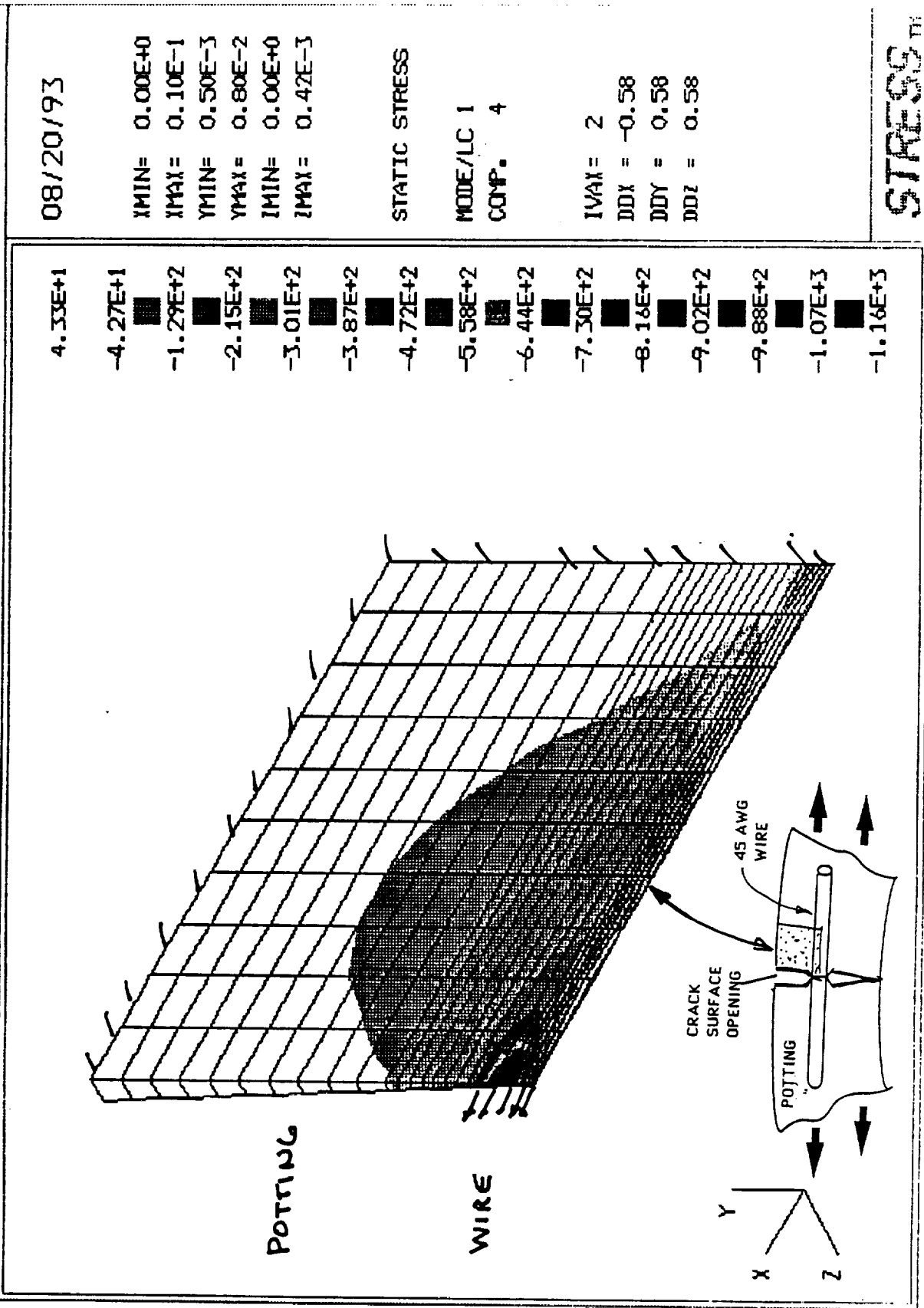
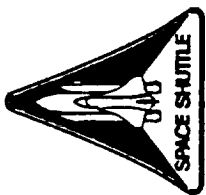


FIGURE 5



# MATERIAL PROPERTIES USED IN ANALYSIS

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	E	CTE	F <sub>ty</sub>	F <sub>tu</sub>
COPPER WIRE	16.	9.	10.	30.
HYSOL CEMENT	1.0	30.	3.	4.
COIL (COMP.)	9.	20.	6.	15.
430 SS	29	10.	30.	65.

FIGURE 6

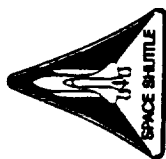


FIGURE 7

STS-51A MAIN ENGINE 2 FUEL FLOW SENSOR ANOMALY  
SENSOR AND DUCT PORT CROSS SECTION

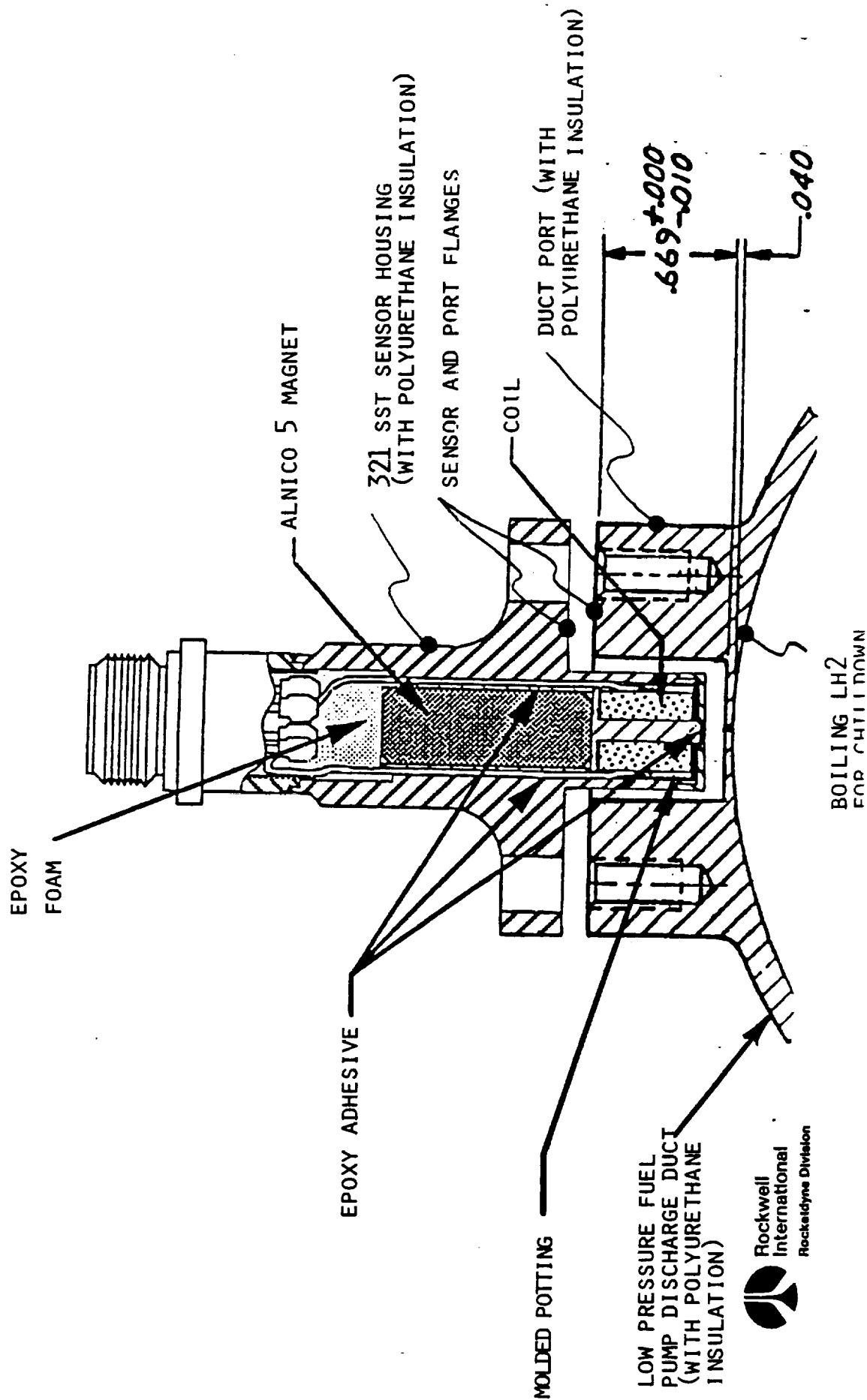


FIGURE 8

# HPFP INLET FUEL FLOW SENSOR ESTIMATED CHILLDOWN TEMPERATURE FOR SENSOR COIL AND HOUSING

LUMPED CAPACITANCE (QUICK) METHOD, CONTACT  $H=500 \text{ BTU/HR-FT}^2\text{-}^\circ\text{R}$

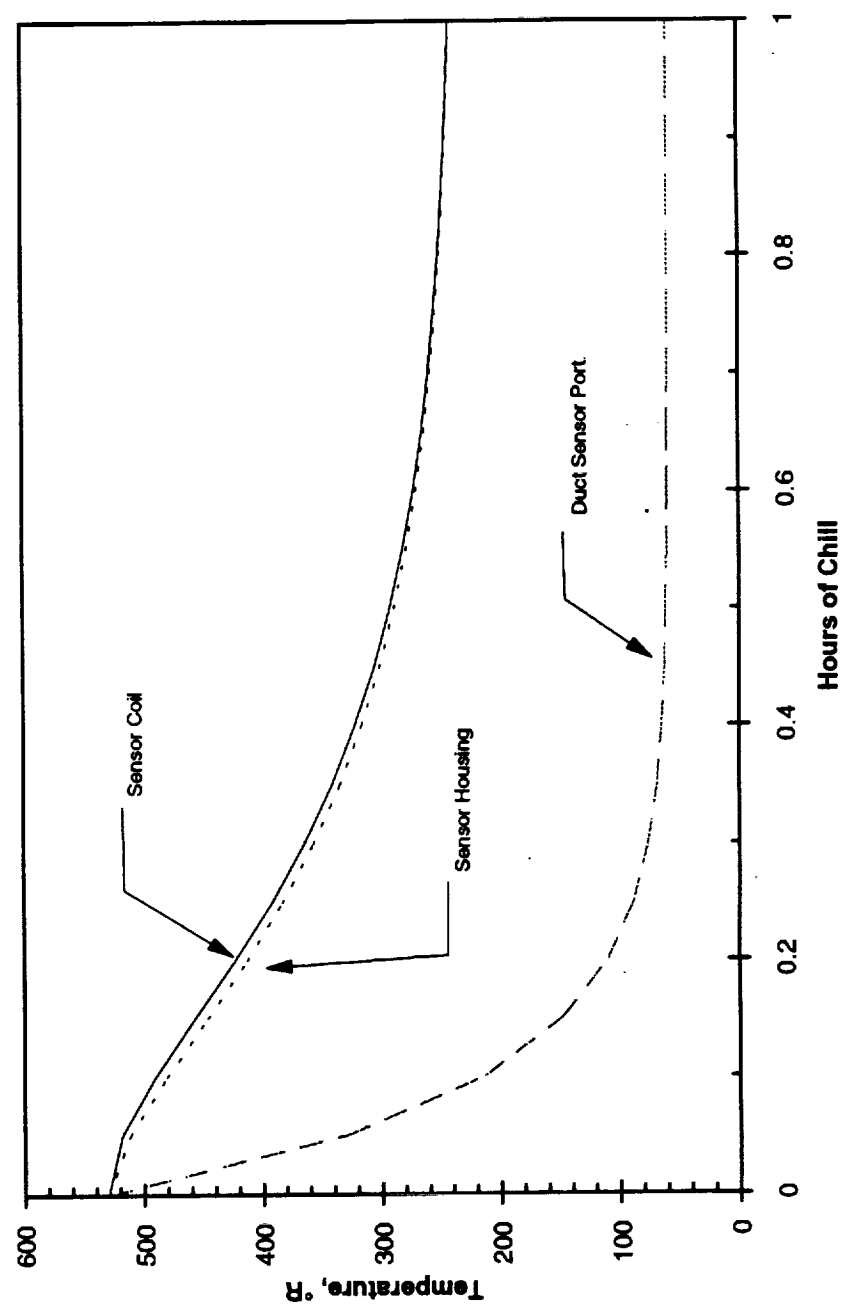
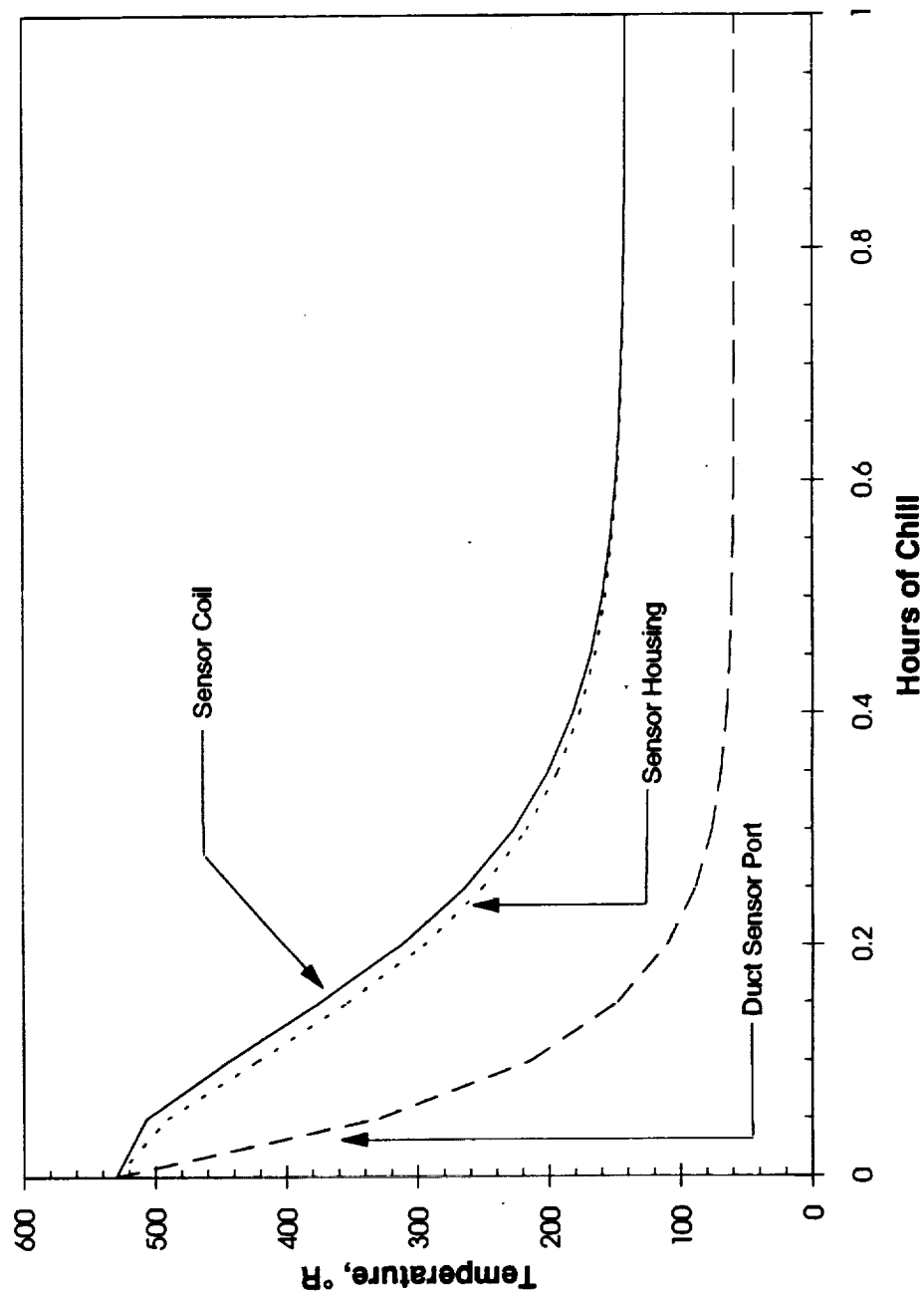


FIGURE 9  
 HPFP INLET FUEL FLOW SENSOR  
 ESTIMATED CHILLDOWN TEMPERATURE FOR SENSOR COIL AND HOUSING  
 LUMPED CAPACITANCE (QUICK) METHOD, CONTACT  $H=1500 \text{ BTU/HR-FT}^2\text{-}^\circ\text{R}$



ANSYS 4.4A  
 AUG 18 1993  
 12:27:26  
 PLOT NO. 1  
 PREP7 ELEMENTS  
 TYPE NUM

ZV = 1  
 DIST = 1.898  
 XF = 1.151  
 YF = 3.564

FIGURE 10  
 HPFP FUEL INLET FLOW SENSOR  
 2-D THERMAL MODEL

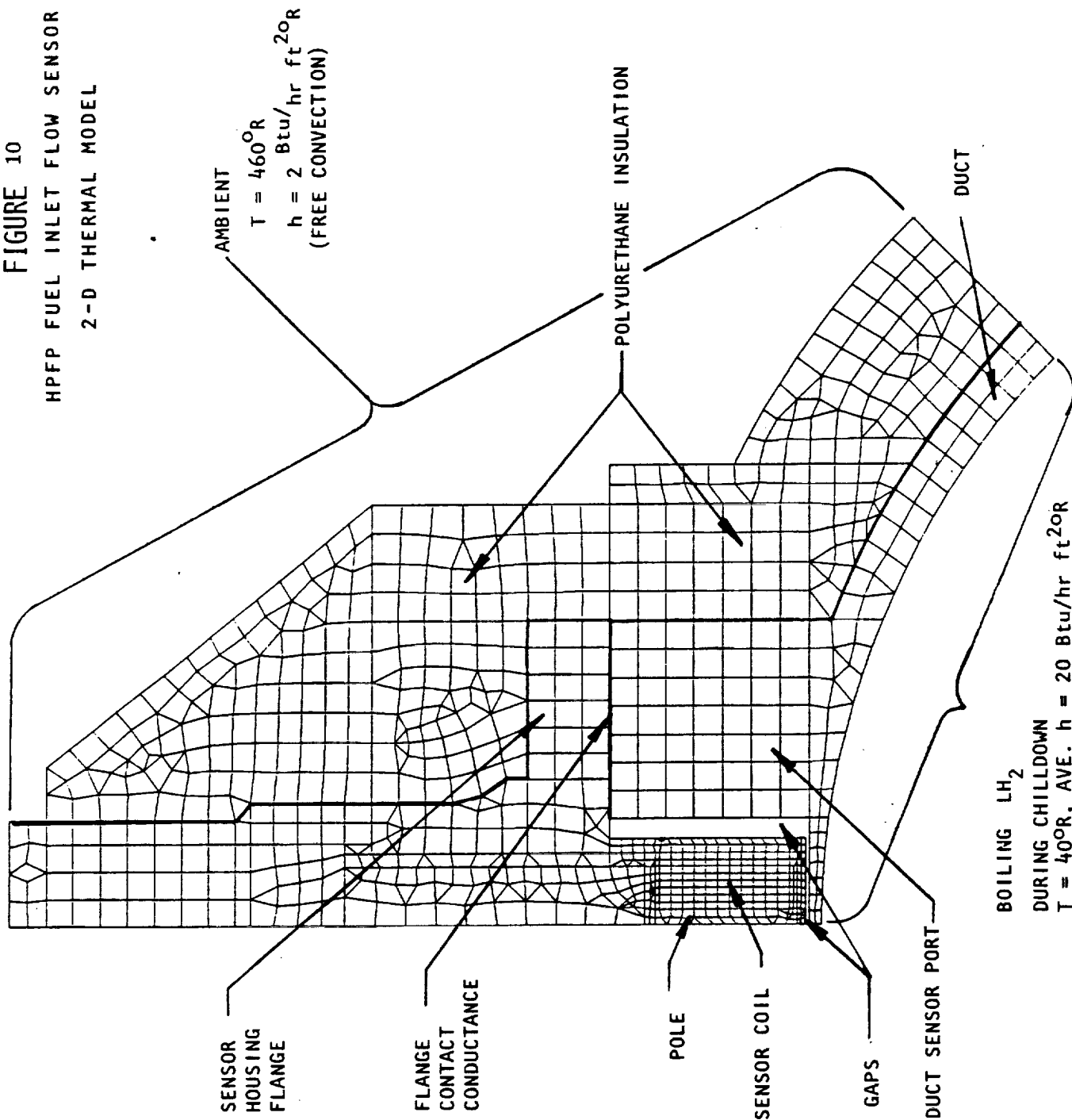


FIGURE 11

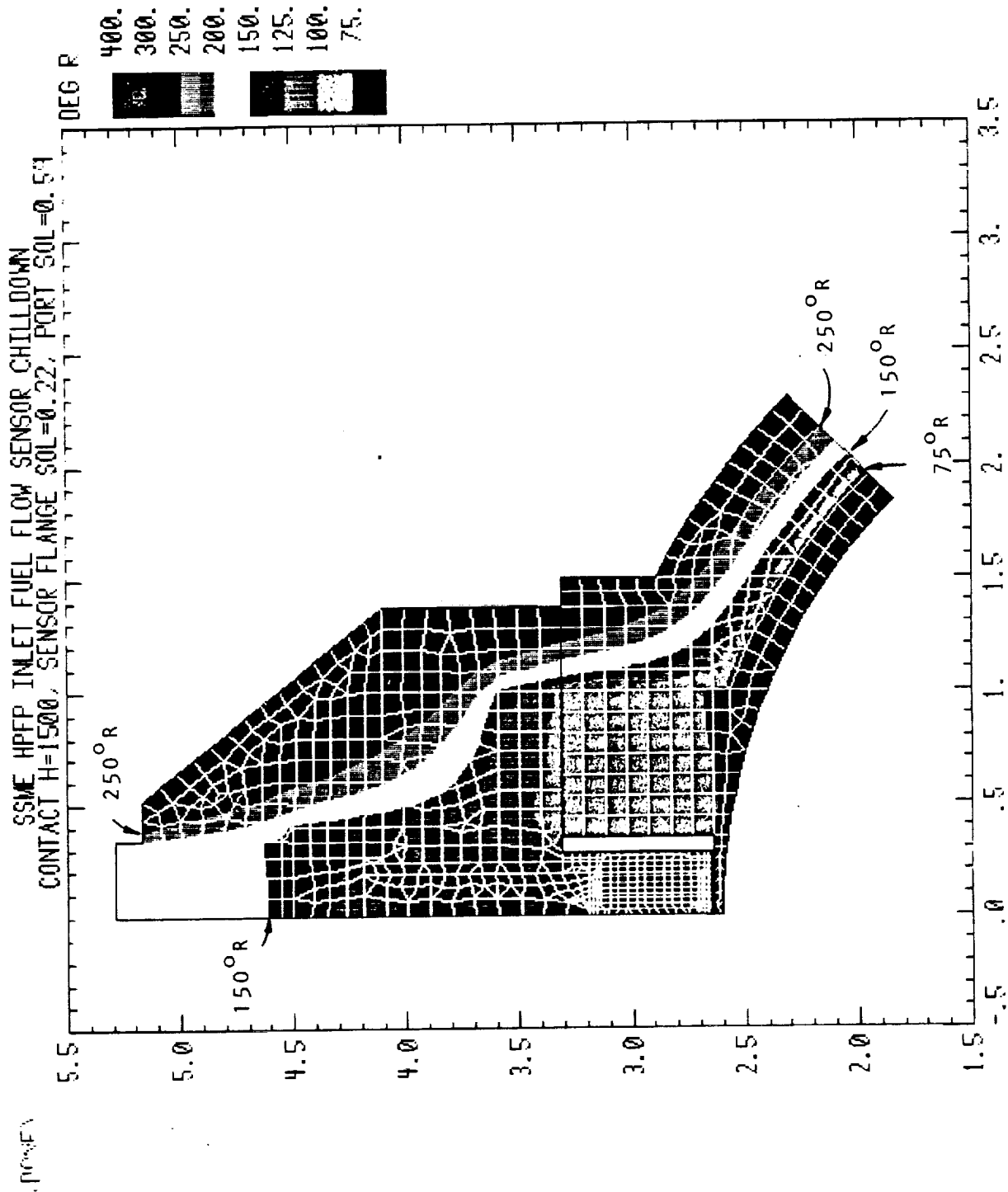


FIGURE 12

SSME HPFP INLET FUEL FLOW SENSOR CHILLDOWN

CONTACT H=1500, SENSOR FLANGE SOL=0.22, PORT SOL=0.59

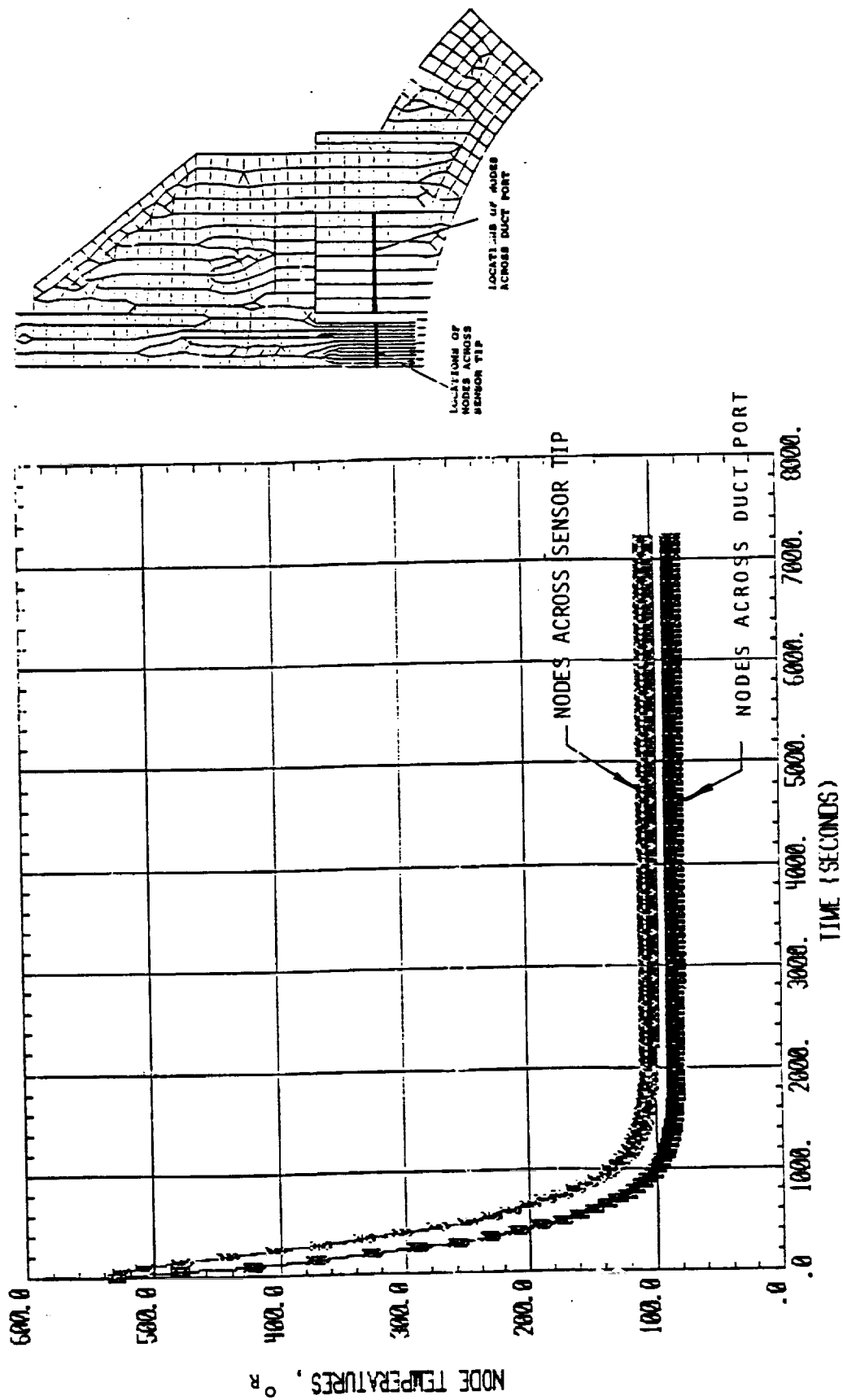
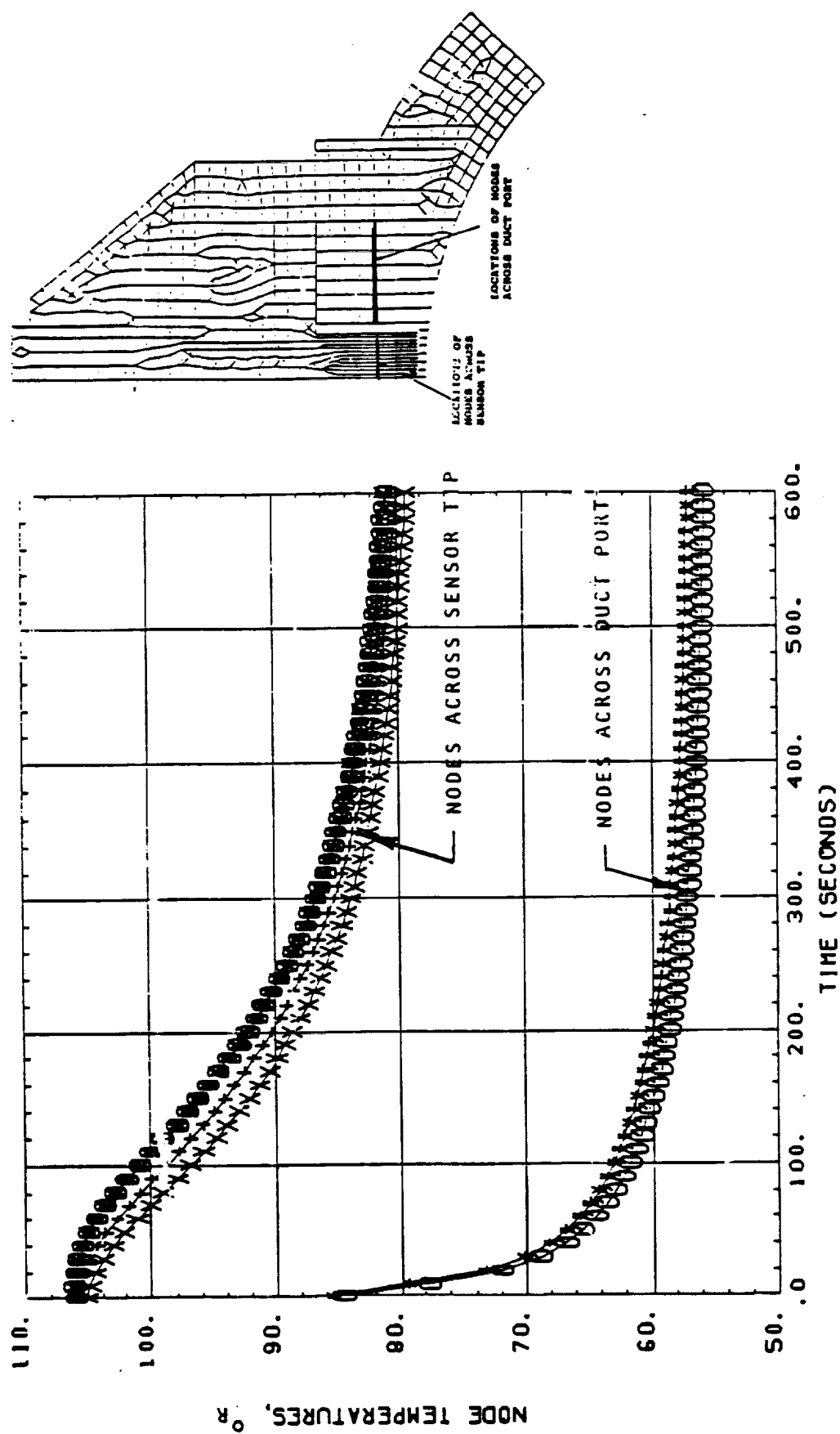




FIGURE 13

SSME HPFP INLET FUEL FLOW SENSOR - MAINSTAGE (600 SECONDS)  
 CONTACT H=1500, SENSOR FLANGE SOL=0.22, PORT SOL=0.59  
 COIL OHMIC HEAT GENERATION = 0.073 BTU/HR



## **Section 7.0**

### **Sensor Failure Correlation**

## **SENSOR FAILURE CORRELATION**

### **FUEL FLOW SENSOR FAILURE CORRELATION**

Open circuit failure history for the flight configuration fuel flow sensor, part number RES7005-051/061, is shown in Figure 1. Twelve sensors have failed out of a population of 313 that were shipped by the manufacturer, Rosemount, Inc. These parts were manufactured over a time span of 1978 to 1990 (Figure 2). The flow sensors have failed on both flight and development engines and only the most recent failure, serial number 2582, caused a launch abort.

Engine hot-fire experience on the failed parts (Figure 3) varies from infant mortality failures due to electrical shorts in the pickup coils to a wide range of time (159 to 25,847 seconds) on sensors that failed due to open circuit. Of the twelve failures, nine were the result of open circuits in the pickup coil and three were due to short circuits in the coil. All but one of the open circuit failures occurred because of a break in the 45 AWG magnet wire. Serial number 2004 failed open circuit due to a fatigue failure in a 32 AWG, stranded leadwire. Of the sensors that received fractography on the broken wires, three magnet wire breaks were attributed to ductile fractures and the one leadwire was a fatigue failure isolated to a workmanship problem.

Beginning with the failure investigation of serial number 2010 in December 1987, the pickup assemblies of failed flow and speed sensors were examined more closely for proper strain relief in the coil wire to leadwire braze joint and for shaved insulation where the leadwire extends into the potted pickup coil. Also, flow sensors built prior to 1980 as RES7005-051 parts received a series of rapid thermal shocks (from room temperature to liquid nitrogen temperature) during the final assembly process. As a result of the failure investigation on serial number 1474, sensors built after 1979 were given gradual thermal cycles.

### **FAILURE CORRELATION ANALYSIS**

The purpose of the Variable Correlation Analysis, performed as part of the Sensor Failure History and Total Variable Summary, was to examine all the available lot traceability data for indicators of sensor susceptibility to failure, and/or predictive trends among the longest-surviving parts. In particular, the correlations identified would be used to estimate the "level of confidence" for each of the existing hot-fire assets (sensors which have been on an SSME during hot-fire testing).

## METHOD

First, a database was created from all the manufacturing and documentation information available from Rosemount for all the fuel flow sensors of the present design, which is represented in two dash numbers that differ only in the nature of the thermal cycling tests performed for workmanship screening.

A graphical display of this data was achieved by making scatter plots of each information field (y-axis) against sensor number (x-axis). Since Rosemount's lot data were alpha-numeric, conversion to purely numeric data was required for analysis purposes. The resulting "Lot Codes" (numbers) were displayed in new columns beside the original lot designations. From the scatter plots, several observations were made: 1. no one information field correlated strongly with even half of the failures (i.e., the lots out of which the failed sensor came usually contained high-performing sensors as well), 2. correlations were non-random (i.e., failures were not evenly distributed among all lot numbers of all lot types), 3. the actual causes of the failures (if deterministic at all) were likely to be indirectly related to several of the information fields, 4. the causal factors are subtle enough that they could not be discerned by viewing the scatter plots alone, 5. some information fields correlated more strongly with failures than others. From this understanding of design and fabrication, the twelve most important variables were chosen and ranked according to importance.

A more rigorous analysis was then undertaken, in which lot statistics for each lot type (e.g. pickup assembly braze lot, final assembly inspection date, hysol lot) were computed for each constituent lot number. A "high confidence lot" was postulated to contain: 1. **minimal failures** (lot has good ratio of #non-failed units to #total units), 2. **maximal "experience"** (units proven through much hot-fire time and many engine starts/thermal cycles), and 3. **large population** (the more units in the lot, the greater the confidence). Averages of the above quantities were computed for each lot in an attempt to quantify the correlation between individual sensor lots (traceability information including lot numbers and/or milestone dates) and the characteristic success rate of each lot type (see appendix for detailed printouts of these statistics). A quantitative scoring method was devised (using a multiplicative combination of the above factors) to rate each lot number of each lot type on a discrete scale of +2, +1, 0, -1, -2.

From this lot rating information, the scores for each of the most important lots which comprise a sensor's build history were displayed on a scoring matrix structured in an analogous way to the original database. A total score was then computed for each sensor from the "hot-fired" population. In particular, each sensor's total "risk assessment score" is a weighted sum of its constituent lot scores, with the weights for the lot types corresponding to their relative importances:

$$S_n = \sum W_i S_i$$

$S_n$  = total score for sensor #n

$W_i$  = weighing factor for variable "i" (e.g. P/A Braze Date)  
 $s_i$  = score for lot of type "i" of which sensor "n" is a part (e.g. Lot T5)

This scoring method was then tested using a sensitivity analysis in which the weighing factors were perturbed and observations made of the resulting split between the averages for the failed sensor group and the highest experience group (each containing a population of about a dozen). Also, the "failed set" was varied, with one run including all 12 failed units in the analysis, another including only the 9 "coil open circuit" failures in the analysis, and a third (the best one) incorporating all but the one failure which (based upon historical details) was considered to be causally unrelated to the others. The summary statistics for this sensitivity analysis were displayed in scatter plots of the averages (and their associated standard deviations) vs. sensitivity "case" number

## RESULTS

The optimized model (using the chosen "failure set" and selected weighing factors) was used to compute final "risk assessment" scores, which are presented in graphical form (Figure 4).

Three categories were noted and defined for use in DAR's intended to make use of the parts (181 hot-fire assets total) most likely to perform well:

1. **"B1" Parts -- High (Scores greater than zero).**  
Defined two "failed group" standard deviations above "failed group" average score, or alternately, one "failed group" standard deviation above B2 group average score; Group includes 108 functional parts.  
Recommended use: flight.
2. **"B2" Parts -- Medium (Scores > -21 and ≤ zero).**  
Defined one "failed group" standard deviation above B3 group average score and one below B1, or alternately, above roughly one "non-failed group" st. deviation of "non-failed" group average score; Group includes 35 functional parts.  
Recommended use: development test monitoring.
3. **"B3" Parts -- Low (Scores ≤ -21).**  
Defined as within one standard deviation of "failed group" average score (which excludes S/N 1296); Group incles 26 functional parts.  
Recommend use: non-flight d~~o~~ channels.

## **SCREENING RECOMMENDATIONS**

### **For Flight Purposes**

1. Risk Assessment Score > zero.
2. Hot-Fire Starts between 5 and 100.
3. Hot-Fire Time between 1,000 and 25,000 sec.

### **For Development Purposes**

1. Risk Assessment Score > -21.

## **MODEL SENSITIVITY ANALYSIS AND OPTIMIZATION**

### **Statistical Method Tested Through Variations of the "Failure Set"**

A "blind run" which incorporated all 12 failed units in the analysis successfully flagged the two units known by analysis history to be relatively unrelated to the other failures.

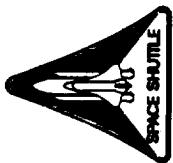
Two other runs compared a statistical model incorporating only the 9 "coil open circuit" failures, with a model (the best one) which included all except the one failure (based upon historical details) considered to be the most causally unrelated to the others.

Among the models, the split between the averages of the failed set and the high-use set was considered to be statistically significant in relation to the scatter in the data, which indicated that the statistical approach could yield useful information about the risk associated with each sensor.

### **Statistical Method Tested and Optimized Through Sensitivity Analysis**

Weighing factors for the variables were optimized from an initial baseline (derived from Rocketdyne sensor engineering experience in conjunction with Rosemount design and manufacturing experience) by testing over 250 different variations and running scores each case.

Observations were made of the resulting statistics (averages, extreme, and standard deviations) for various categories (failed sensors, moderate use sensors, and highest experience sensors), and optimized weighing factors selected.



# FUEL FLOW SENSOR FAILURE HISTORY

FUEL FLOW SENSOR OPEN CIRCUIT FAILURES DUE TO CRACKED POTTING				
S/N	HOT FIRE		HOT FIRE DATE	PHASE DETECTED
	STARTS	SECONDS		
905	11	2713	06-79	POST SHUTDOWN
1399	5	159	10-79	93 SECONDS
1474	3	352	09-80	PRESTART
2010	3	772	12-87	10 SECONDS
2211	2	532	08-89	PRESTART
1969	71	12897	10-90	CHECKOUT
2186	61	25847	02-91	PRESTART
2004	30	14438	07-92	START
2583	8	2437	08-93 (STS-51A)	START
				OPEN @ AMBIENT
				OPEN @ AMBIENT
				OPEN @ AMBIENT
				OPEN @ AMBIENT
				FAIL LN <sub>2</sub> TEST
				OPEN @ AMBIENT
				OPEN @ AMBIENT
				FAIL LN <sub>2</sub> TEST
				FAIL LN <sub>2</sub> TEST

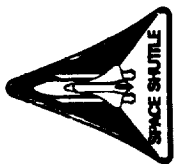
FIGURE 1

# SSME FUEL FLOW SENSOR-FAILURE HISTORY

S/N and UOR	DATE OF MFG.	FAIL DATE	TEST/SECONDS	FAIL COIL	FAIL TEMP	FAILURE ANALYSIS	BREAK LOCATION	STRAIN RELIEF?	SHAVED LEADS?	RAPID LN2 INVERSION?
915	Oct-78	Mar-79 E2004	0/0	NFD	AMB	SHORTED COILS ABRAIDED INS.	N/A			YES
A010859										
905	Oct-78	Jun-79 E2004	11/2,713	B-1	AMB	OPEN COIL POTTING CRACK	COIL #1			YES
A018815										
1399	May-79	Oct-79 E0105	5/159	A-1	AMB	OPEN COIL POTTING CRACK	COIL #1			YES
A009792										
1296	May-79	Jun-88 E2029	1/1.5	B-1	LN2	SHORTED COILS	N/A	YES	NO	YES
A020605										
1474	Sep-79	Sep-80 E2008	3/352	NFD	AMB	OPEN COILS EXCESSEPOXY	BOTH COILS			YES
A017887										
1969	Jun-82	Oct-90 E0208	71/12,897	NFD-2	AMB	OPEN COIL DUCTILE FRAC.	COIL #2	NO	YES	NO
A030140										
2004	Sep-82	Jul-92 E0218	30/14,438	A-2	LN2	OPEN COIL FATIGUE	LEADWIRE TO COIL #2	YES	SLIGHT	NO
A031838										
2010	Sep-82	Dec-87 E2028	3/772	B-1	LN2	OPEN COIL FATIGUE	COIL #1	NO	YES	NO
A014365										
2186	Jul-83	Feb-91 E0213	61/25,847	NFD	AMB	OPEN COIL DUCTILE FRAC.	COIL	YES	PARTIAL	NO
A030569										
2210	Aug-83	Dec-83 2021	1/1.5	COIL 2	AMB	SHORTED COIL NOT CONFIRMED	N/A			NO
A012239										
2211	Aug-83	Aug-89 E2024	2/532	NFD-1	250F	OPEN COIL POTTING CRACK	COIL #1	NO	YES	NO
A022723										
2582	Jan-90	Aug-93 E2033	8/2436	A-2	LN2	OPEN COIL DUCTILE FRAC.	COIL #2 HIGH(+) SIDE	YES	NO	NO
A032605										

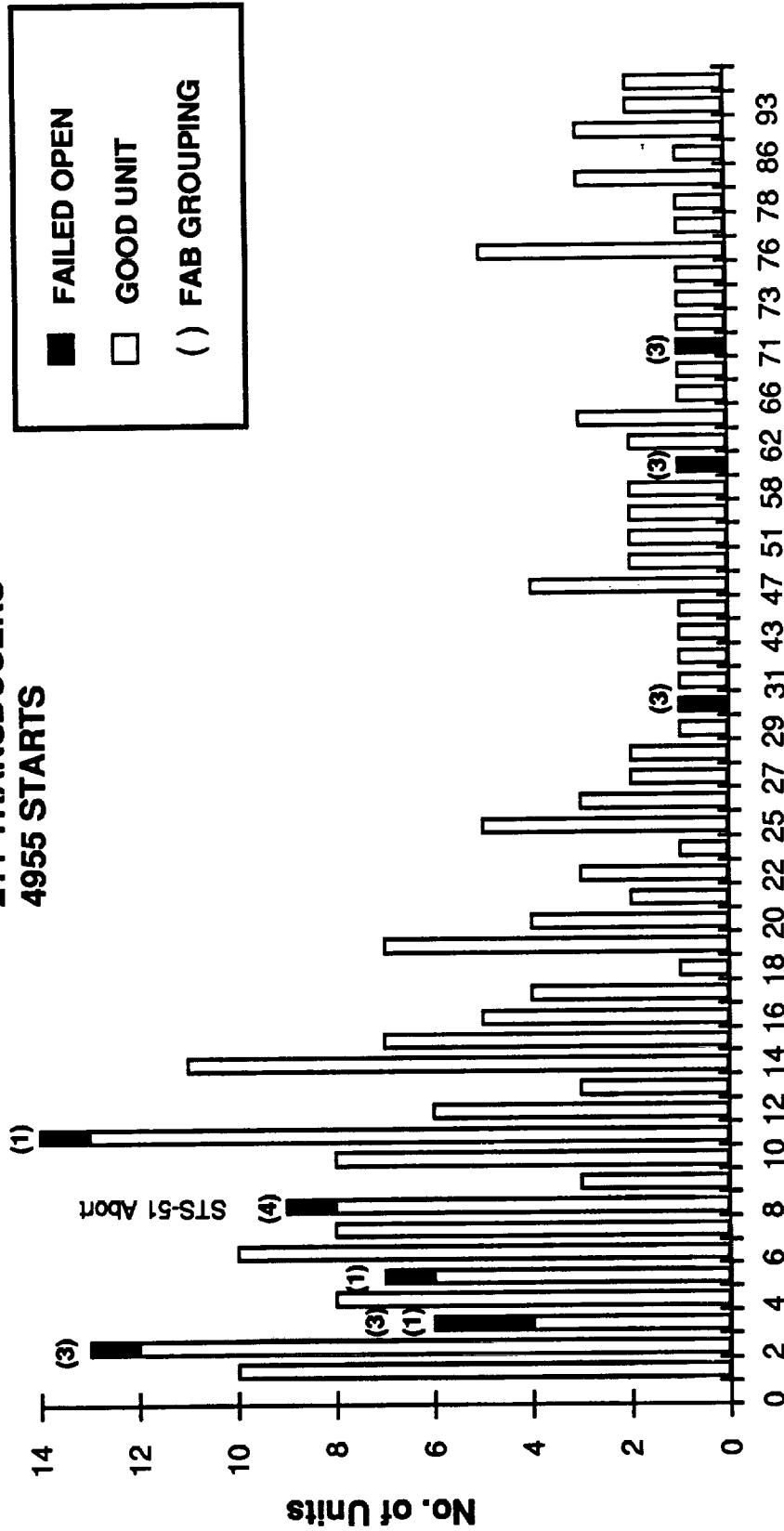
FIGURE 2





# SSME FUEL FLOW SENSOR HISTORY

211 TRANSDUCERS  
4955 STARTS



No. of Starts

FIGURE 3

# SSME Flow Sensor Traceability--Risk Scores (10/18/93)

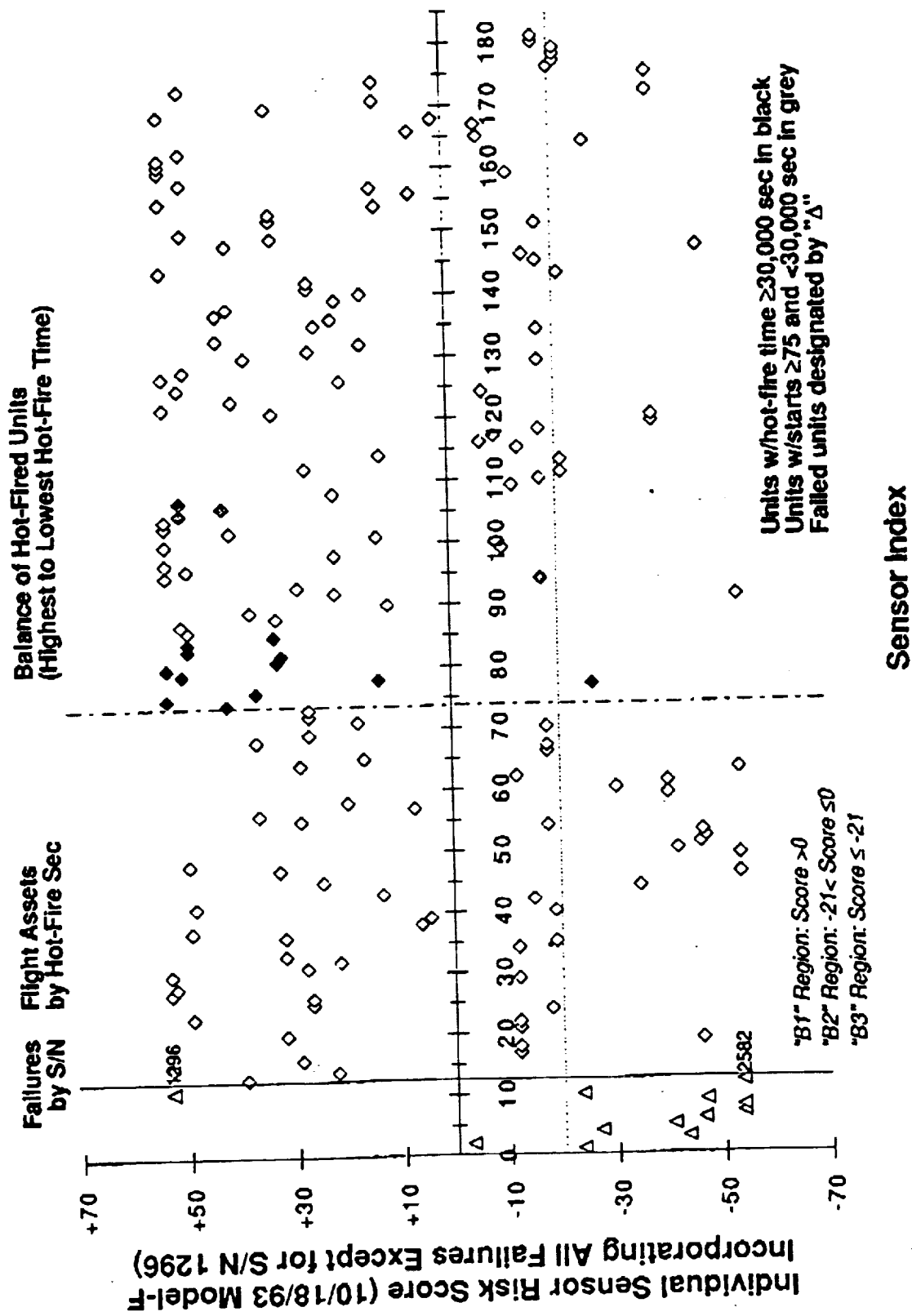


FIGURE 4

## **Section 8.0**

### **Software Change**

## SOFTWARE CHANGE

### SOFTWARE CHANGE SUMMARY

The SSME incorporates two separate flow sensors on each engine. Each flow sensor includes two pickup coils. All four pickup coils are used to compute an average hydrogen flowrate for use in mixture ratio control. The previous software monitored all four coils on each engine (total of 12 per launch) against limits defining a "GOOD" or "BAD" coil. Any identified "BAD" coil prior to launch caused disqualification of a sensor coil pair (two coils) and a pad abort (STS-51 8/12/93 attempt).

The new software provides a flow reference computation to which each of the four coils can be compared such that "BAD coils can be disqualified one at a time. The software permits one failed coil (on each engine) prior to launch without aborting the launch, and the engine flies with three good coils.

The revised flow validation software was originally planned as part of a new software block update called OI-6. It's inclusion in OI-6 was a result of a similar sensor failure in ground test in July 1992. The software was defined for OI-6 in Jan. 1993 and in verification at the Huntsville Simulation Lab (HSL) at MSFC since March 1993.

The software modification after the STS-51 abort merely lifts the OI-6 flow validation change already in verification for four months as part of OI-6 and adapts it to OI-5 using the identical logic. Other non-related changes as part of OI-6 would not complete verification until November 1993 and precluded its use.

The revised OI-5 software has been exposed to all software verification requirements, 1185 total test cases including all hypothesized failure modes. The new verification requirements match a new software version but really represent a second verification, the first as part of OI-6. In addition, an independent assessment and audit is being performed by MSFC. Certification will include three engine hotfire tests on a minimum of two engines before committing to flight. One of those tests will include operation of the engine with a failed coil to verify the software response and subsequent engine operation simulating pre liftoff operation. Post equivalent liftoff will include an artificial failure in the controller to validate the software response to that failure.

### SOFTWARE CHANGE DISCUSSION

The software in use during the STS-51 Pad Abort launch attempt was designated RRS902M01AAAA24. This software is also referred to as OI-5 version AA24 for the

Block II Controller and has been used on all flights since STS-52. The fuel flow sensor qualification logic used in this version is the same as all prior Block II Controller software versions. The requirements for this logic were derived from the Block I Controller software requirements.

The AA24 fuel flow sensor qualification monitors are summarized in Figures 1 and 2. The significant features of this version are the four different monitors that become active at different times, the Inhibit (pre-start only) and resumable MCF responses for the first failure, and the disqualification of sensors as pairs as well as individually. The command from the Orbiter to shutdown on the pad originated from the MCF in the failure response of the first fuel flow intra-channel failure prior to SRB ignition. This test detected the output failure of sensor A2 when it differed from sensor A1 by more than 1800 gpm for three consecutive updates.

Prior to the STS-51 pad abort, the potential for a fuel flow sensor failure was recognized and a software change was already in work for the OI-6 software version to reduce the risk, (Figure 3). The logic change had already been designed, developed, and validation tested at the Huntsville Simulation Laboratory (HSL) at MSFC. It was scheduled for STS-62 in February 1994. The only remaining effort was completion of testing at HSL for other changes contained in the OI-6 version and hot fire certification testing at the Stennis Space Center.

One of the actions of the Pad Abort Investigation was to initiate modification of the AA24 software to include the fuel flow sensor qualification logic in the OI-6. All of the requirement change, design, development, software test and hot fire test activities were performed on a priority basis to produce a new OI-5 software version designated RRS902M01AAAA35 (AA35). The ECP for this change was approved and all required lab and hot fire verification testing was successfully completed including a coil failure simulation and power bus failure in hot fire, (Figure 4).

The purpose of the fuel flow sensor logic change is to better utilize the redundancy of the four available flow sensors. The concept is to qualify the sensors individually instead of in pairs and raise the failure responses up to the next redundancy element. The result of this change allows liftoff if at least 3 of the 4 sensors are functioning. The AA35 fuel flow qualification monitors are summarized in Figures 5 and 6. The significant differences from the previous version are the deletion of the intra-channel, inter-channel, and sensor reasonableness tests, the addition of a calculated reference flowrate value ( $Q_{ref}$ ) for comparison with the individual sensors, and the elimination of the Inhibit and MCF responses for the first failure of either the sensor qualification test or the Pulse Rate Converter (PRC) update test. If this software had been in use when the STS-51 pad abort occurred, the failure of the flow sensor would have been detected and reported by the PRC update test at about 3.0 seconds after engine start but because of no MCF in the failure response, no shutdown would have been commanded. The mission would have continued normally with the three remaining

good sensors.

The modified OI-5 software version AA35 allows launch with one fuel flowmeter sensor channel failure during engine start. This logic change also modifies the qualification method of the flow sensor channels prestart. Instead of comparing the intrachannel (A1, A2 or B1, B2) to be within 1800 gpm, the individual sensor channels are qualified to Q reference and must be within 0 and 1800 gpm. Failure of the first channel prestart will cause the controller to issue a report only FID, a MCF is posted for the second sensor channel failure. Since a report only FID is not visible to the GPC or ground system computers, a preplanned contingency procedure for launch commit criteria (SSME-29) was established for STS-51.

This procedure monitors the fuel flow sensor channels manually. If the report only FID is posted during prelaunch conditioning prior to engine start and is caused by actual fuel flowmeter motion as a result of tanking or MPS operations, then a controller reset can be issued to clear the FID and proceed with the countdown for launch. It is also noted in the procedures that a controller reset will cause the engine bleed valves to close, therefore requiring a 60 minutes of continuous bleed flow prior to engine start to maintain a proper start sequence. The countdown is to be scrubbed if the FID is reported and is not related to the LH2 system because the failure implies an electronics malfunction within the controller circuitry, (Figure 7). A FID occurring between APU start and T-31 seconds will result in a launch scrub condition since there is insufficient time for discussion. This procedure was accepted by the Shuttle management team for STS-51 based on the relative MTBF's described in Figure 8. Because of the possibility of false failure indications, an examination of the flow measurement system failure modes was made to determine the possible meanings of pre-launch failure indications. It was found in the nominal no-flow pre-launch conditions that sensor and harness failures are not detectable. The only detectable hardware failure is an intermittent failure in the controller PRC electronics. It was also found that propellant system operations during the pre-launch period could create false failure indications.

In order for the software to distinguish between these failure indications and reject the false ones, it is assumed that a qualification failure is not a PRC failure unless the failure is persistent. If the failure is not persistent, sensor qualification strikes are cleared and no failure will be reported. This logic was included in the AA37 software because it minimizes the possibility of reporting false failures and the need to perform a controller reset in order to restore a falsely disqualified sensor.

A revision to modify the software response to a resumable MCF for the first fuel flow sensor failure prior to engine start is planned for the subsequent flights. This will allow the ground system computers to monitor for the MCF automatically and eliminate the need for a manual monitoring of the launch commit criteria.

# FUEL FLOWRATE MONITOR

## QUALIFICATION

### OI-5 AA24

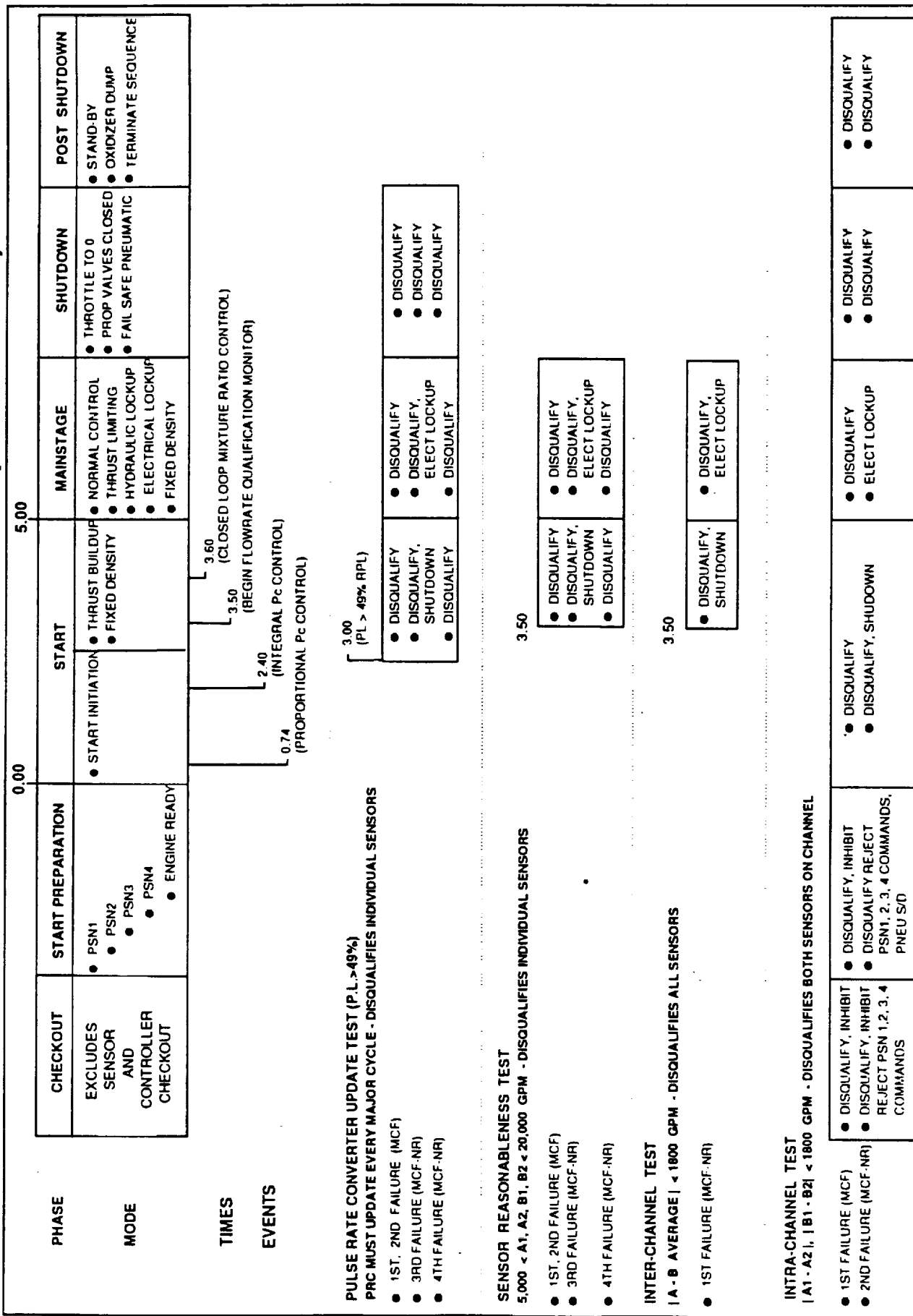
MONITOR PERIOD		MONITOR DESCRIPTION	RESPONSE	ENGINE STATUS WORD
BEGIN	END			
CHECK OUT (1)	—	<ul style="list-style-type: none"> <li>FUEL FLOWRATE INTRA-CHANNEL TEST</li> <li>• <math> A1-A2 ,  B1-B2  &lt; 1800 \text{ GPM}</math></li> </ul>	1ST FAILURE- • DISQUALIFY CHANNEL, INHIBIT 2ND FAILURE- • DISQ. CHANNEL, INHIBIT, REJECT PSN1-4 COMMANDS	MCF MCF-NR
PSN1	E/S	<ul style="list-style-type: none"> <li>FUEL FLOWRATE INTRA-CHANNEL TEST</li> <li>• <math> A1-A2 ,  B1-B2  &lt; 1800 \text{ GPM}</math></li> </ul>	1ST FAILURE- • DISQUALIFY CHANNEL, INHIBIT 2ND FAILURE- • DISQ. CHANNEL, REJECT PSN1-4 COMMANDS, PNEU S/D	MCF MCF-NR
E/S	E/S +3.48 SEC	<ul style="list-style-type: none"> <li>PULSE RATE CONVERTER UPDATE TEST (P.L.&gt;49%)</li> <li>• PRC MUST UPDATE EVERY MAJOR CYCLE (A1,A2,B1,B2)</li> </ul>	1ST,2ND FAILURE- • DISQUALIFY SENSOR 3RD FAILURE- • DISQUALIFY SENSOR • SHUTDOWN (START) OR ELECTRICAL LOCKUP (M/S) 4TH FAILURE- • DISQUALIFY SENSOR	MCF MCF-NR MCF-NR
E/S +3.50 SEC	S/D	<ul style="list-style-type: none"> <li>FUEL FLOWRATE INTRA-CHANNEL TEST</li> <li>• <math> A1-A2 ,  B1-B2  &lt; 1800 \text{ GPM}</math></li> </ul>	1ST FAILURE- • DISQUALIFY CHANNEL 2ND FAILURE- • DISQUALIFY CHANNEL • SHUTDOWN (START) OR ELECTRICAL LOCKUP (M/S)	MCF MCF-NR
		<ul style="list-style-type: none"> <li>PULSE RATE CONVERTER UPDATE TEST (P.L.&gt;49%)</li> <li>• PRC MUST UPDATE EVERY MAJOR CYCLE (A1,A2,B1,B2)</li> <li>FUEL FLOWRATE REASONABLENESS TEST</li> <li>• <math>5,000 &lt; A1,A2,B1,B2 &lt; 20,000 \text{ GPM}</math></li> </ul>	1ST,2ND FAILURE- • DISQUALIFY SENSORS 3RD FAILURE- • DISQUALIFY SENSOR • SHUTDOWN (START) OR ELECTRICAL LOCKUP (M/S) 4TH FAILURE- • DISQUALIFY SENSOR	MCF MCF-NR MCF-NR
		<ul style="list-style-type: none"> <li>FUEL FLOWRATE INTER-CHANNEL TEST</li> <li>• <math> A \text{ AVG} - B \text{ AVG}  &lt; 1800 \text{ GPM}</math></li> </ul>	1ST FAILURE- • DISQUALIFY BOTH CHANNELS	MCF-NR
		<ul style="list-style-type: none"> <li>FUEL FLOWRATE INTRA-CHANNEL TEST</li> <li>• <math> A1-A2 ,  B1-B2  &lt; 1800 \text{ GPM}</math></li> </ul>	1ST FAILURE- • DISQUALIFY CHANNEL 2ND FAILURE- • DISQUALIFY CHANNEL • SHUTDOWN (START) OR ELECTRICAL LOCKUP (M/S)	MCF MCF-NR
S/D	POST S/D	<ul style="list-style-type: none"> <li>PULSE RATE CONVERTER UPDATE TEST (P.L.&gt;49%)</li> <li>• PRC MUST UPDATE EVERY MAJOR CYCLE (A1,A2,B1,B2)</li> </ul>	1ST,2ND FAILURE- • DISQUALIFY SENSOR 3RD FAILURE- • DISQUALIFY SENSOR 4TH FAILURE- • DISQUALIFY SENSOR	MCF MCF-NR MCF-NR
		<ul style="list-style-type: none"> <li>FUEL FLOWRATE INTRA-CHANNEL TEST</li> <li>• <math> A1-A2 ,  B1-B2  &lt; 1800 \text{ GPM}</math></li> </ul>	1ST FAILURE- • DISQUALIFY CHANNEL 2ND FAILURE- • DISQUALIFY CHANNEL	MCF MCF-NR
POST S/D	—	<ul style="list-style-type: none"> <li>FUEL FLOWRATE INTRA-CHANNEL TEST</li> <li>• <math> A1-A2 ,  B1-B2  &lt; 1800 \text{ GPM}</math></li> </ul>	1ST FAILURE- • DISQUALIFY CHANNEL 2ND FAILURE- • DISQUALIFY CHANNEL	MCF MCF-NR

(1) NOT ACTIVE DURING SENSOR CHECKOUT OR CONTROLLER CHECKOUT  
 • INTRA-CHANNEL TEST FAILURE REQUIRES 3 CONSECUTIVE PRC UPDATED STRIKES  
 • PRC, REASONABLENESS TESTS FAILURE REQUIRE 3 CONSECUTIVE MAJOR CYCLE STRIKES

FIGURE 1

FFRQLM2.TBL

# FUEL FLOW RATE MONITOR (OI-5 AA24)



(MONITOR DRAW)

FIGURE 2





# SSME FLIGHT SOFTWARE CHANGE

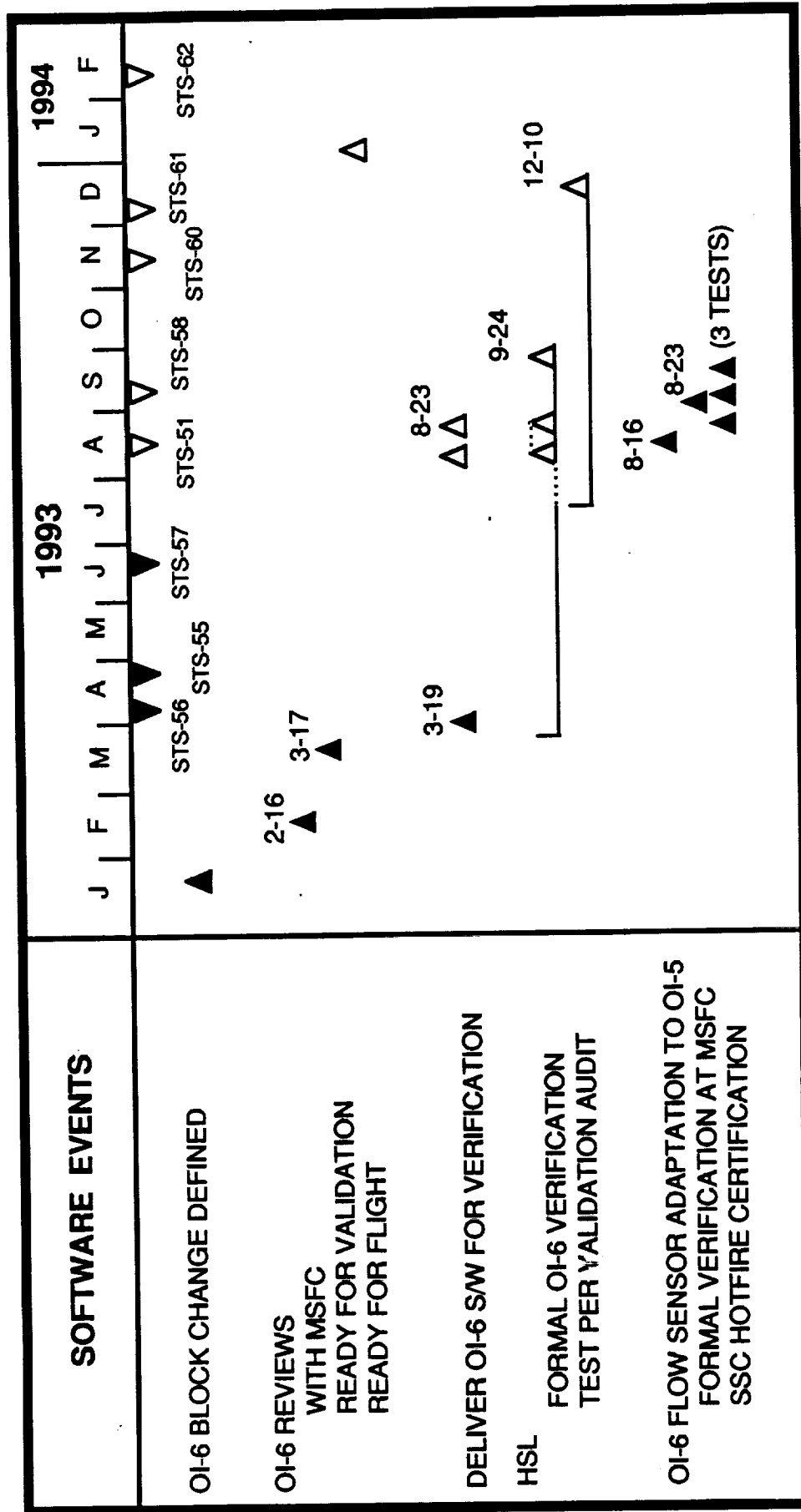
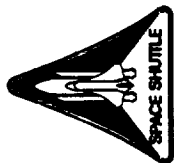


FIGURE 3



# SOFTWARE VERIFICATION HOT-FIRE

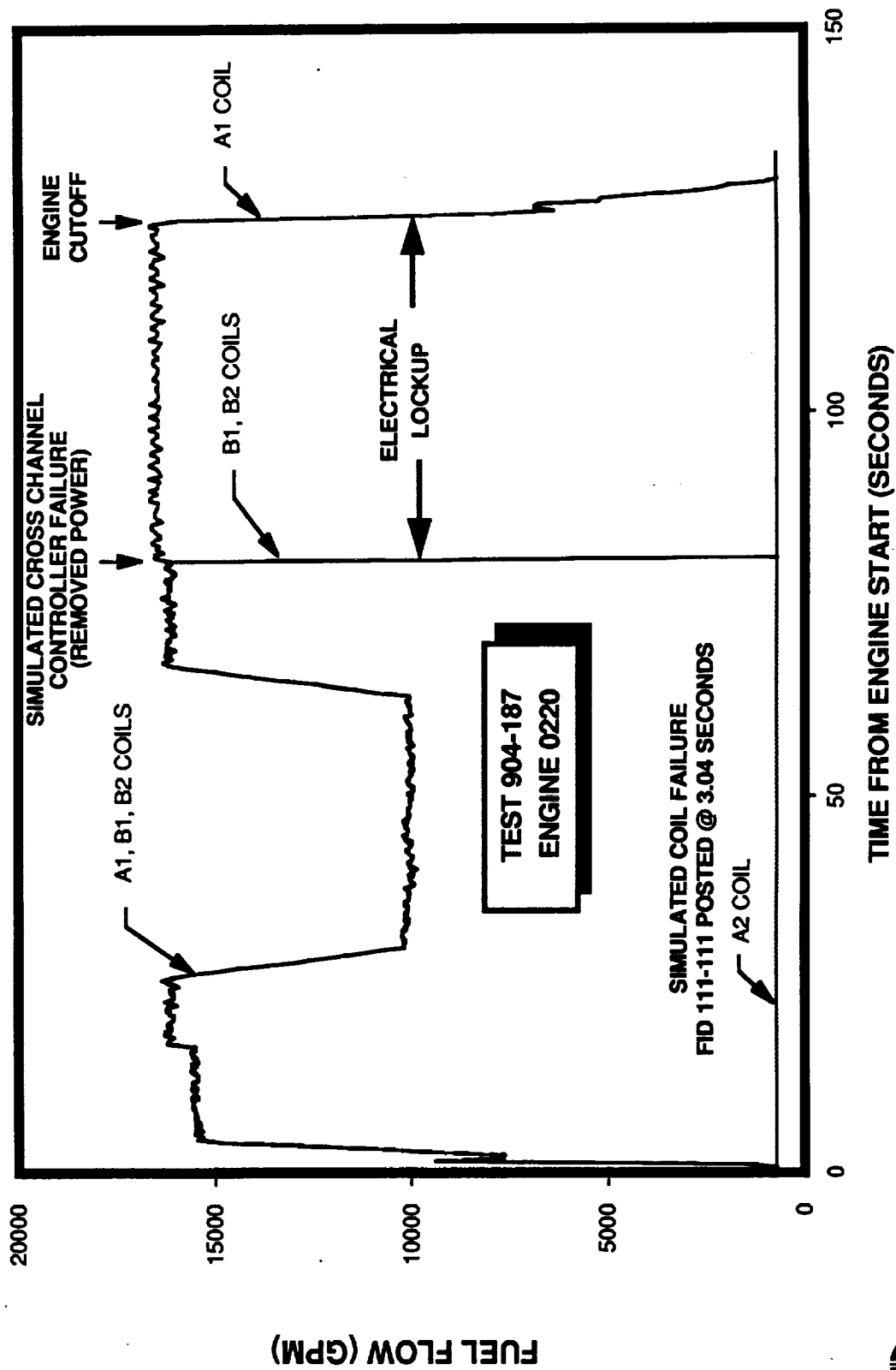


FIGURE 4

# FUEL FLOWRATE MONITOR

## QUALIFICATION

### OI-5 AA35

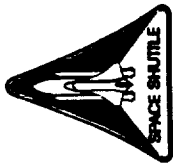
MONITOR PERIOD		MONITOR DESCRIPTION	RESPONSE	ENGINE STATUS WORD
BEGIN	END			
CHECK OUT	—	<ul style="list-style-type: none"> <li>• NONE</li> </ul>		
PSN1 (1)	E/S	<ul style="list-style-type: none"> <li>• FUEL FLOWRATE QUALIFICATION TEST</li> <li>• <math>0 &lt; (A1,A2,B1,B2) - Q_{ref} &lt; 1800 \text{ GPM}</math></li> <li>• <math>Q_{ref} = 0</math></li> </ul>	1ST FAILURE- DISQUALIFY SENSOR 2ND FAILURE- DISQUALIFY SENSOR, INHIBIT 3RD FAILURE- DISQUALIFY SENSOR, REJECT PSN1-4 COMMANDS, PNEU S/D 4TH FAILURE- DISQUALIFY SENSOR	--- MCF MCF-NR MCF-NR
E/S	E/S +3.48 SEC	<ul style="list-style-type: none"> <li>• PULSE RATE CONVERTER UPDATE TEST (P.L.&gt;49%)</li> <li>• PRC MUST UPDATE EVERY MAJOR CYCLE (A1,A2,B1,B2)</li> </ul>	1ST FAILURE- DISQUALIFY SENSOR	---
E/S +3.50 SEC	M/S	<ul style="list-style-type: none"> <li>• PULSE RATE CONVERTER UPDATE TEST (P.L.&gt;49%)</li> <li>• PRC MUST UPDATE EVERY MAJOR CYCLE (A1,A2,B1,B2)</li> <li>• FUEL FLOWRATE QUALIFICATION TEST</li> <li>• <math>0 &lt; (A1,A2,B1,B2) - Q_{ref} &lt; 3600 \text{ GPM}</math></li> </ul>	2ND FAILURE- DISQUALIFY SENSOR 3RD FAILURE- DISQUALIFY SENSOR, SHUTDOWN 4TH FAILURE- DISQUALIFY SENSOR	MCF MCF-NR MCF-NR
M/S	S/D	<ul style="list-style-type: none"> <li>• PULSE RATE CONVERTER UPDATE TEST (P.L.&gt;49%)</li> <li>• PRC MUST UPDATE EVERY MAJOR CYCLE (A1,A2,B1,B2)</li> <li>• FUEL FLOWRATE QUALIFICATION TEST</li> <li>• <math>0 &lt; (A1,A2,B1,B2) - Q_{ref} &lt; 1800 \text{ GPM}</math></li> </ul>	1ST FAILURE- DISQUALIFY SENSOR 2ND FAILURE- DISQUALIFY SENSOR 3RD FAILURE- DISQUALIFY SENSOR, ELECTRICAL LOCKUP 4TH FAILURE- DISQUALIFY SENSOR	--- MCF MCF-NR MCF-NR
S/D	POST S/D	<ul style="list-style-type: none"> <li>• PULSE RATE CONVERTER UPDATE TEST (P.L.&gt;49%)</li> <li>• PRC MUST UPDATE EVERY MAJOR CYCLE (A1,A2,B1,B2)</li> </ul>	1ST FAILURE- DISQUALIFY SENSOR 2ND FAILURE- DISQUALIFY SENSOR 3RD FAILURE- DISQUALIFY SENSOR 4TH FAILURE- DISQUALIFY SENSOR	--- MCF MCF-NR MCF-NR
POST S/D	—	<ul style="list-style-type: none"> <li>• FUEL FLOWRATE QUALIFICATION TEST</li> <li>• <math>0 &lt; (A1,A2,B1,B2) - Q_{ref} &lt; 1800 \text{ GPM}</math></li> </ul>	1ST FAILURE- DISQUALIFY SENSOR 2ND FAILURE- DISQUALIFY SENSOR 3RD FAILURE- DISQUALIFY SENSOR, REJECT PSN1-4 COMMANDS, PNEU S/D 4TH FAILURE- DISQUALIFY SENSOR	--- MCF MCF-NR MCF-NR

(1) • FUEL FLOWRATE QUALIFICATION TEST FAILURE REQUIRES 3 CONSECUTIVE PRC UPDATED STRIKES  
 • PRC UPDATE TEST FAILURE REQUIRES 3 CONSECUTIVE MAJOR CYCLE STRIKES

FIGURE 5



84



# SENSING SYSTEM

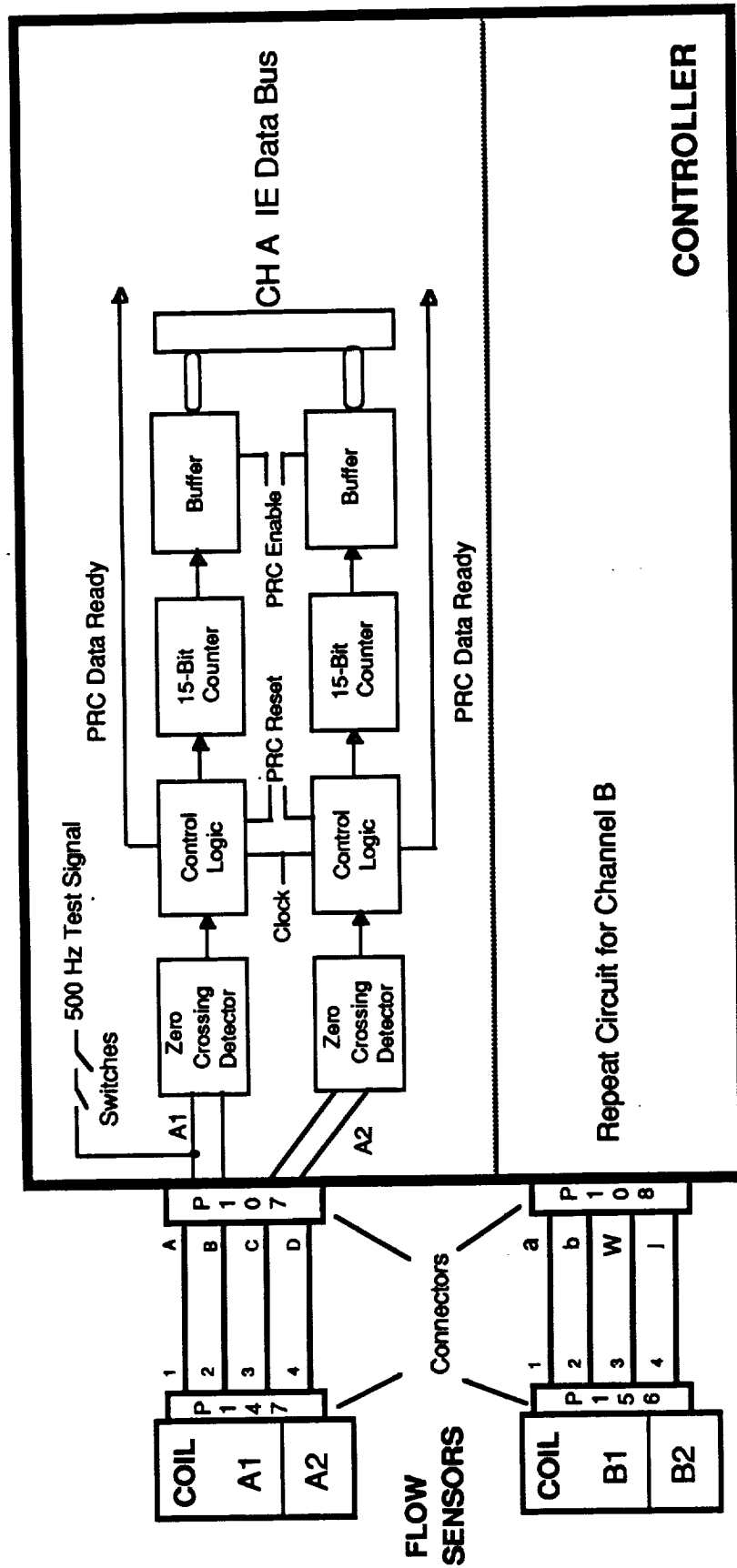
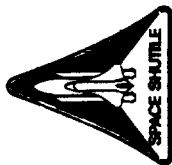
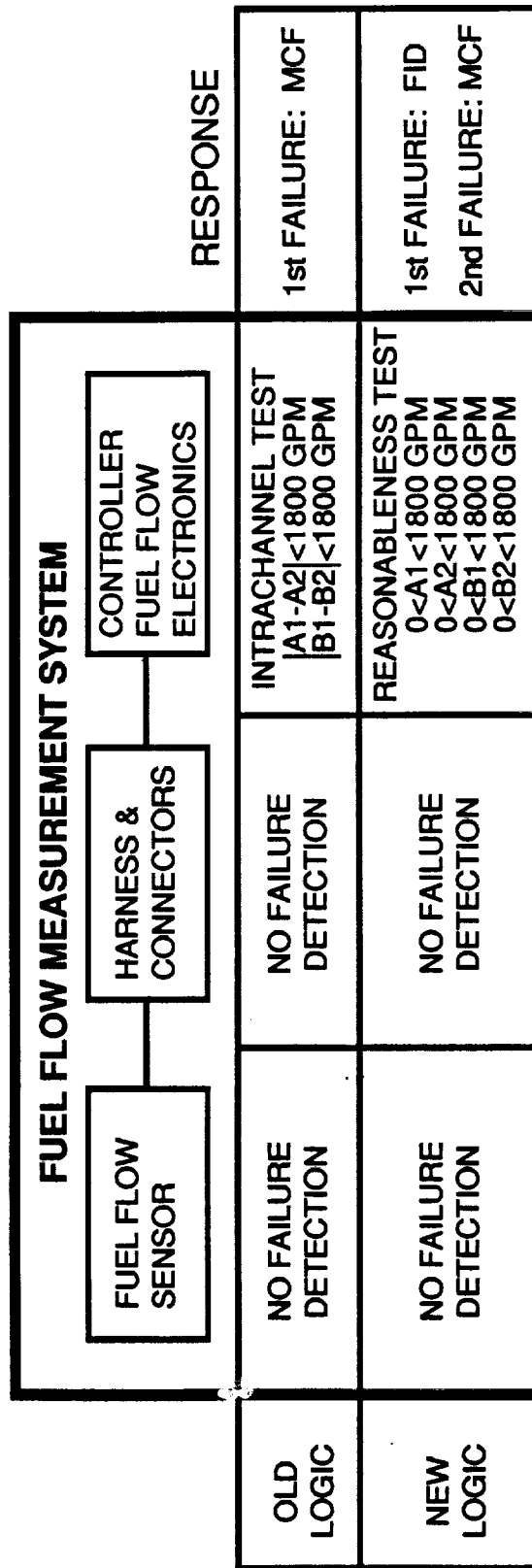


FIGURE 7



# FUEL FLOW SENSING MONITOR LOGIC PRELAUNCH LOGIC COMPARISON



PROBABILITY OF CONTROLLER FUEL FLOW ELECTRONICS FAILURE		ACTION
TIME	FLIGHT MTBF	
T-34 HOURS TO T-5 MIN	1 IN 4,456	SCRUB IF NOT MPS RELATED
T-5 MIN TO T-31 SEC	1 IN 1,800,000	SCRUB
T-31 SEC TO T <sub>0</sub>	1 IN 7,200,000	NO ACTION
T <sub>0</sub> TO MECO	1 IN 135,000	ACTIVE

FIGURE 8

## **Section 9.0**

### **MTBF Comparison**

## **MTBF COMPARISON**

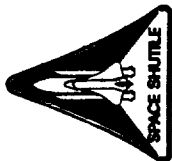
### **FAILURE PROBABILITY (MTBF) IMPACT**

Table 1 depicts the gain associated with the software modification. By allowing liftoff with one of four sensors failed per engine the pad abort MTBF (best estimate) increases from one in 92 flights (using all nine experienced failures) to one in 67,000 flights.

With the revised software, liftoff can occur with one sensor already failed. The vehicle is then one failure away from Electrical Lockup because subsequent failure of the cross channel Input Electronics would disqualify two more flow sensors. An assessment of the probability of Electrical Lockup was performed to determine the severity of this concern. Failure probabilities for the orbiter electrical power buses as well as each engine controller must be considered Figure 1. One power bus failure affects two separate engine controllers via their respective input electronics which in turn affects two flow sensor coils each. One power bus failure will result in four flow coil failures.

The results of this study are presented in Table 2 and indicates the overall risk of Electrical Lockup increases from 1 in 827,000 flights to 1 in 536,000 flights. It was the opinion of the SASCB that the reduced pad abort risk outweighed the increase in the risk of Electrical Lockup after liftoff. This opinion provided the rationale for approval of the AA35 software.





# SYSTEM ASSESSMENT

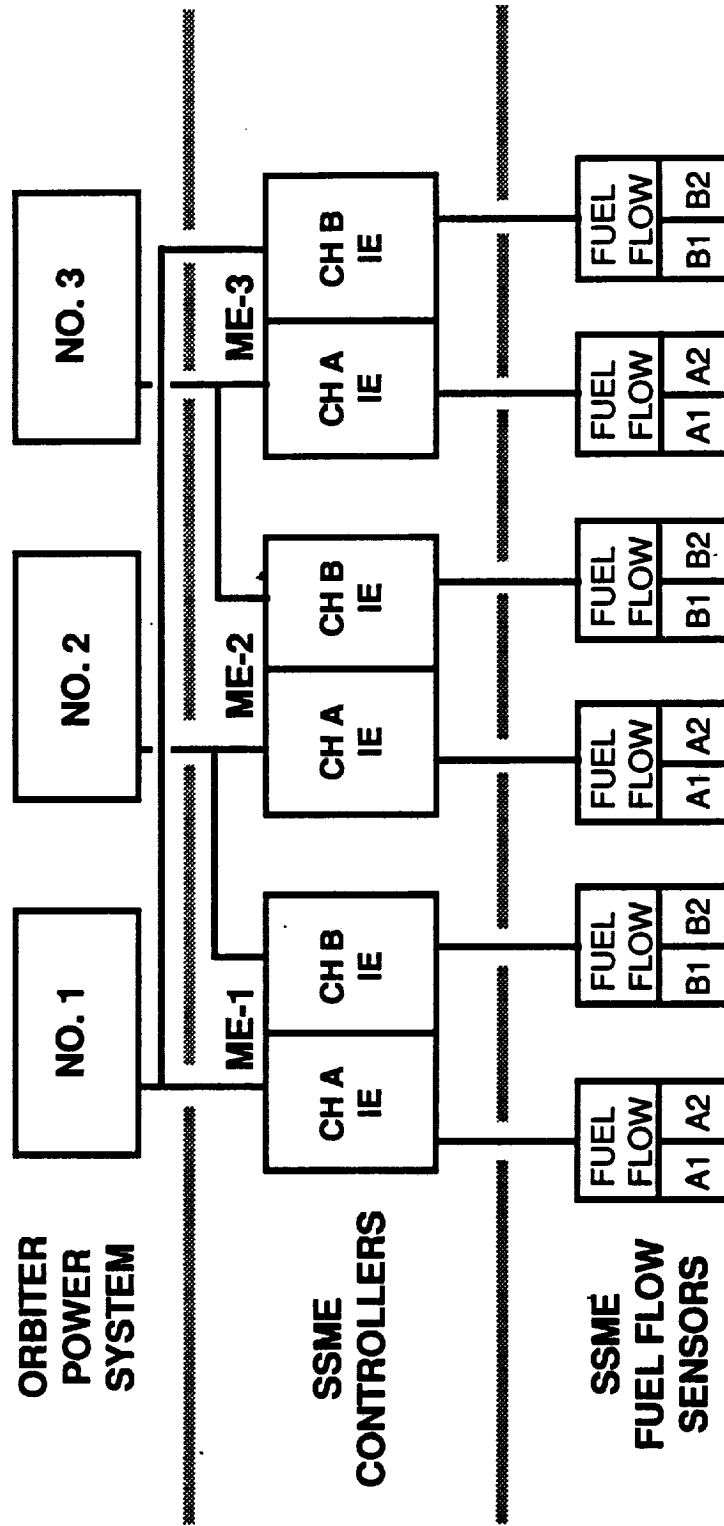


FIGURE 1

## PAD ABORT MTBF

**DATABASE: 9 FAILURES, 9910 STARTS, 2,480,000 SECONDS**

	BEST ESTIMATE	90% CONFIDENCE
<b>EXISTING OI-5 SOFTWARE</b> <ul style="list-style-type: none"> <li>PAD ABORT (1 OF 12 FAIL)</li> </ul>	92	58
<b>MODIFIED OI-5 SOFTWARE</b> <ul style="list-style-type: none"> <li>PAD ABORT (2 OF 4 FAIL ON ANY OF THREE FAILURES)</li> </ul>	67,000	27,000

**TABLE 1**

# ELECTRICAL LOCKUP MTBF

NO	1st FAILURE		2nd/3rd FAILURE		ENGINE MTBF	VEHICLE MTBF
	CAUSE	MTBF	CAUSE	MTBF		
MODES UNAFFECTED BY SOFTWARE CHANGE, COMBINED 1 IN 827,000						
1	LOSS OF 1 OF 3 VEHICLE POWER BUSES	7692	LOSS OF 1 OF 4 CROSS CHANNEL FUEL FLOW COILS	132	N/A	1.0M
2	1 OF 2 CONTROLLER IE CHANNELS FAIL	90,000	1 OF 2 FUEL FLOW COILS FAIL AFTER LIFTOFF	265	24M	8.0M
3			3 OF 4 FUEL FLOW COILS FAIL AFTER LIFTOFF	N/A	37M	12M
ADDITIONAL RISK DUE TO SOFTWARE CHANGE, COMBINED 1 IN 1,526,000						
1	LOSS OF 1 OF 4 FUEL FLOW COILS BEFORE LIFTOFF	276	LOSS OF CROSS CHANNEL VEHICLE POWER BUS	<sup>(1)</sup> 23,000	6.3M	2.1M
2	1 OF 4 FUEL FLOW COILS FAIL BEFORE LIFTOFF	276	2 OF 3 FUEL FLOW COILS FAIL AFTER LIFTOFF	94,000	26M	8.6M
3	1 OF 4 FUEL FLOW COILS FAIL BEFORE LIFTOFF	276	CROSS CHANNEL CONTROLLER IE FAILS AFTER LIFTOFF	<sup>(2)</sup> 179,000	49M	16M

TOTAL COMBINED RISK IS 1 IN 536,681

- (1) BASED ON ORBITER POWER SUPPLY MTBF - 7692 FLIGHTS  
(2) BASED ON ONE CONTROLLER IE FAILURE IN 179,000 CHANNEL HOTFIRE SECONDS

TABLE 2

## **Section 10.0**

### **Hazards / FMEA CIL Impact**

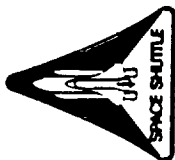
## HAZARDS / FMEA CIL IMPACT

Disqualification of two fuel flow sensor channels during start is addressed as a cause for vehicle commanded shutdown due to an MCF. This is documented in hazard report ME-G6A (Abnormal Thrust Loads) paragraph 2B1. Failure of both sensors (A&B) or one sensor channel (during prestart, start, or mainstage) and the cross-channel IE during mainstage are covered as causes for electrical lockup. This is documented in hazard report ME-G4M (Loss of Thrust) paragraph 2B.

The software logic changes enhance safety risk by greatly reducing the probability of a pad abort while maintaining a very low probability of attaining electrical lockup during mainstage.

The FMEA/CIL has been updated to show the software related/engine effects of the revised software logic. No additional failure modes were identified as a result of the software change (Figure 1). These are reflected in the controller, harness and sensor FMEA/CILS. The effects of these failure modes are already covered in Hazard Reports ME-G6A and ME-G4M. There is no impact to the hazard analysis.

Intermittent fuel flow electrical output signals, resulting in off-nominal mixture ratio operation, are also identified as criticality 1R failure modes in the FMEA/CIL(s). The effects of these failure modes are already covered in Hazard Reports ME-G6A and ME-G4M as "erroneous redline shutdown".



# FMEA/CIL REQUIREMENTS

LRU	PART NAME	FAILURE MODES	PHASE	CRIT
J601 J602	FUEL FLOW SENSORS	<ul style="list-style-type: none"> <li>• NO ELECTRICAL OUTPUT SIGNAL</li> <li>• INTERMITTENT ELECTRICAL OUTPUT SIGNAL</li> </ul>	PRESTART  START  MAINSTAGE CUTOFF  DUMP	3  1R  1R 3  3

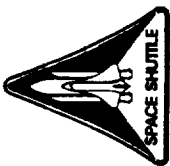
## **Section 11.0**

### **NASA Level-I and STS-51 L-2 Closeout Briefing**

## **NASA LEVEL-I AND STS-51 L-2 CLOSEOUT BRIEFING**

The results of the team investigation were presented by Byron Wood to the NASA Level I PRCB via telecon on 8/24/93 and to the Mission Management Team (STS-51 L-2 Day) on 9/10/93 at KSC. The investigation findings and rationale to fly STS-51 (OV103) were included in the presentation.





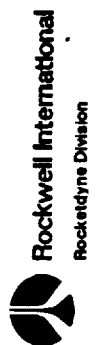
STS-51

## PAD ABORT INVESTIGATION

~~9/8/93~~

8/24/93 Level I Telecon  
9/10/93 STS-51 L-2

ROCKETDYNE



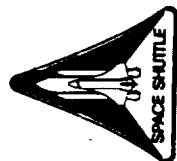
1



## STS-51 PAD ABORT INVESTIGATION

- **ISSUE**
  - PAD ABORT DUE TO LOSS OF FUEL FLOW SENSOR REDUNDANCY
- **BACKGROUND**
  - NO OUTPUT FROM ME-2 FUEL FLOW SENSOR DURING START
    - STS-51 LAUNCH ATTEMPT 8/12/93
  - MAJOR COMPONENT FAILURE (MCF) DUE TO INTRACHANNEL CHECK VIOLATION AT START +1.34 SECONDS S/D @ 1.5 SEC
  - FUEL FLOW SENSOR HISTORY
    - 8 STARTS/2437 SECONDS
    - 3 PRIOR FLIGHTS STS-46, 54 & 56
  - ENGINE OPERATION NORMAL & SOFTWARE RESPONSE AS DESIGNED

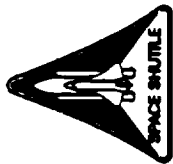
START 3, 2, 1		<u>Abort</u>		<u>Decision To Replace Engines 8/12/93</u>	
ME-1	2030	3.84	2031		2
-2	2033	1.50	2034		
-3	2032	2.80	2029		



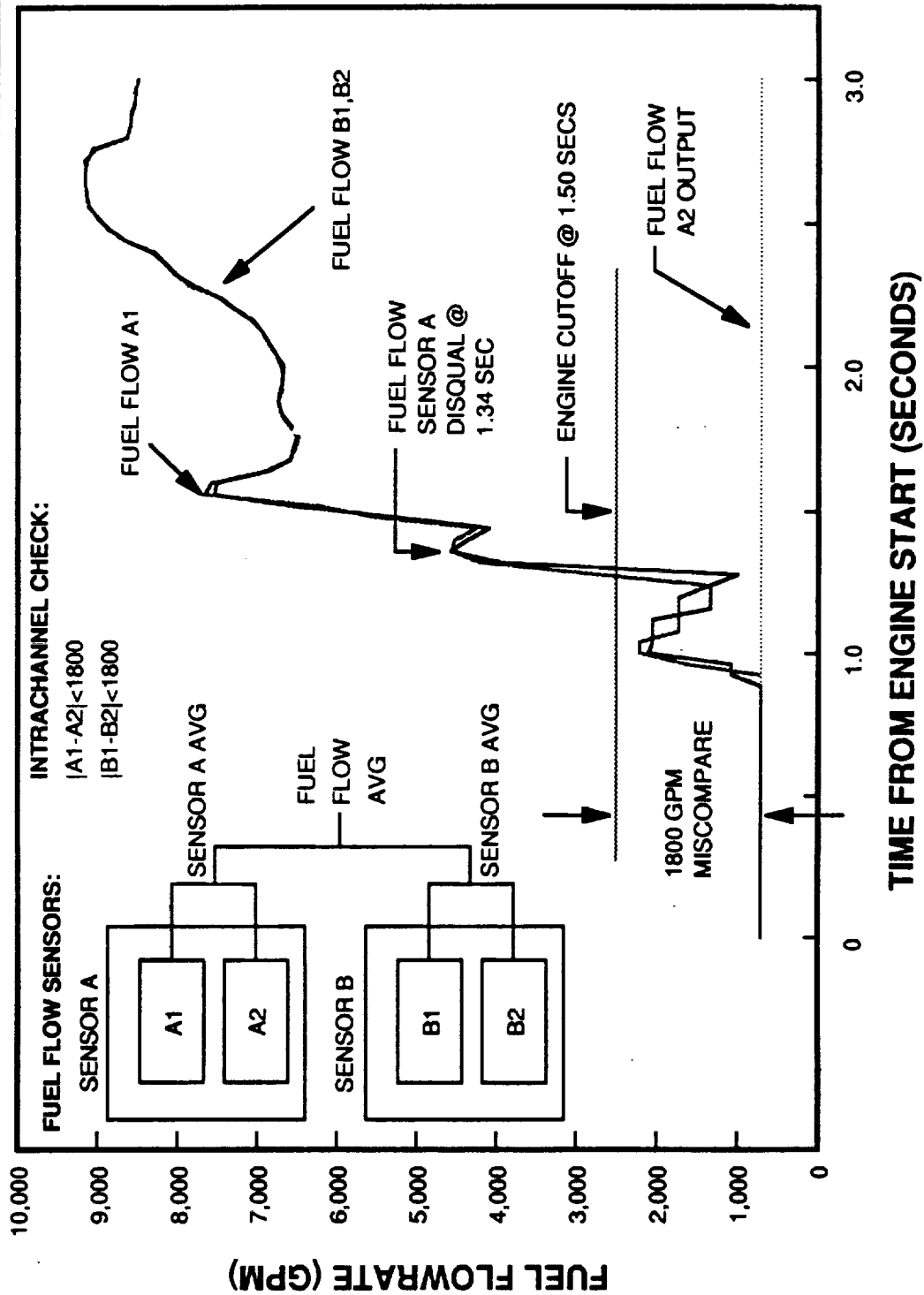
# FMEA/CIL REQUIREMENTS

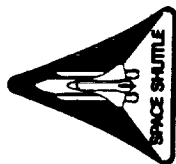
LRU	PART NAME	FAILURE MODES	PHASE	CRIT
J601 J602	FUEL FLOW SENSORS	<ul style="list-style-type: none"> <li>• NO ELECTRICAL OUTPUT SIGNAL</li> <li>• INTERMITTENT ELECTRICAL OUTPUT SIGNAL</li> </ul>	PRESTART  START  MAINSTAGE  CUTOFF  DUMP	3  1R  1R  3  3

FLOWFMEA

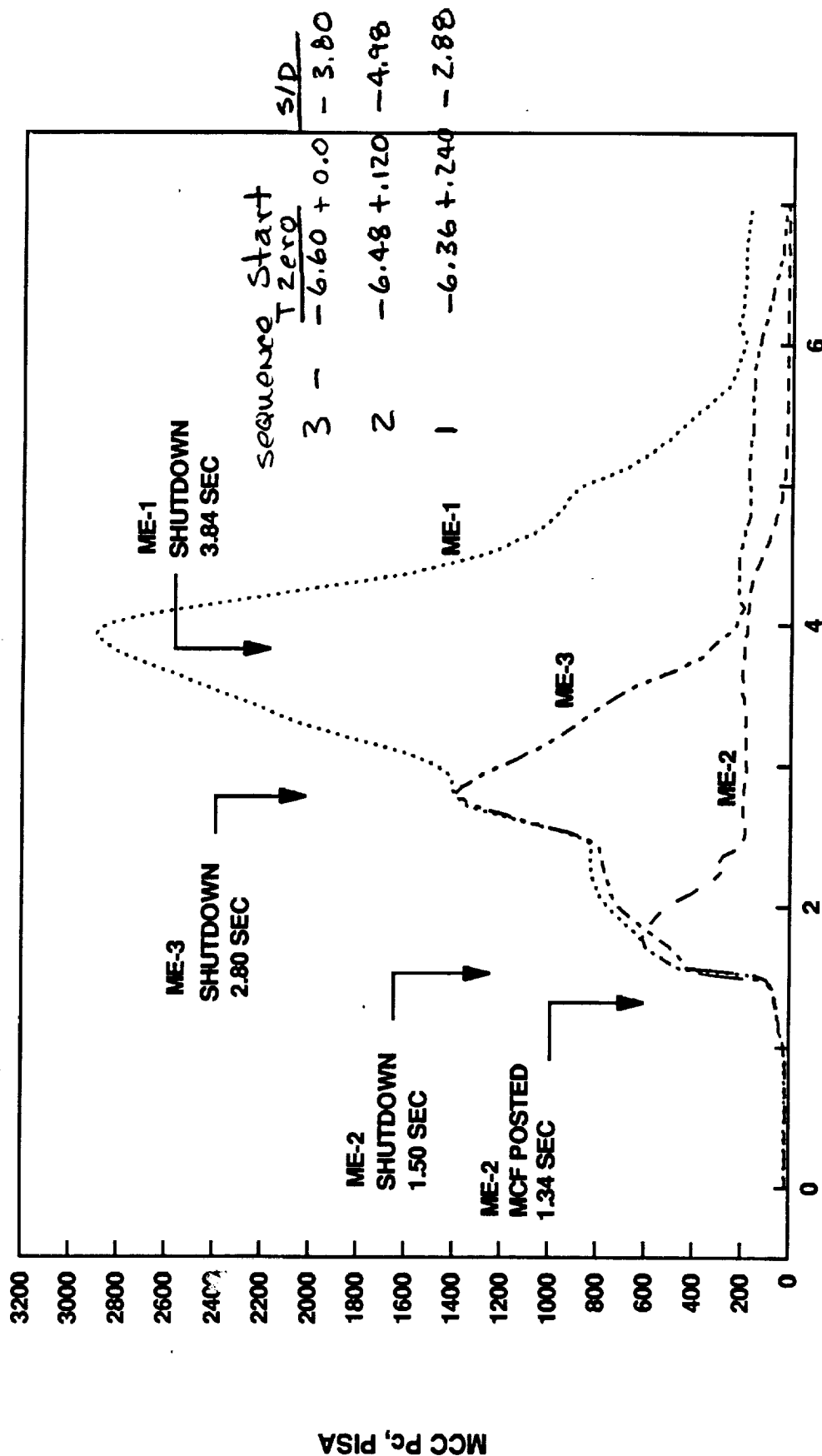


# STS-51 ABORT FLOW SENSOR DATA

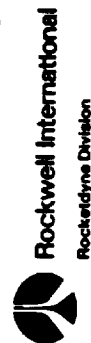




# ENGINE PERFORMANCE NOMINAL



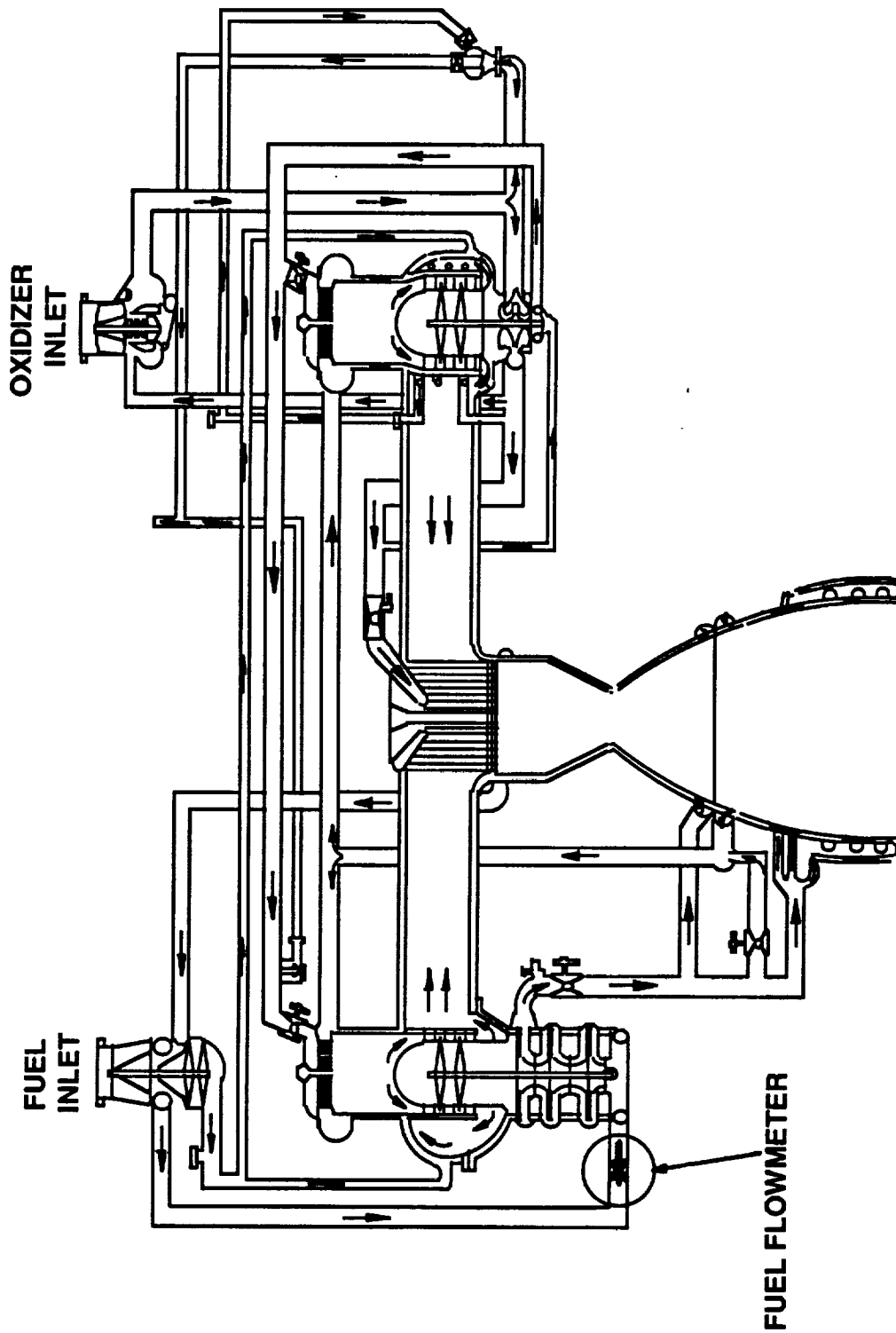
51LVJ3D3884-BG



TIME FROM ENGINE START, SECONDS

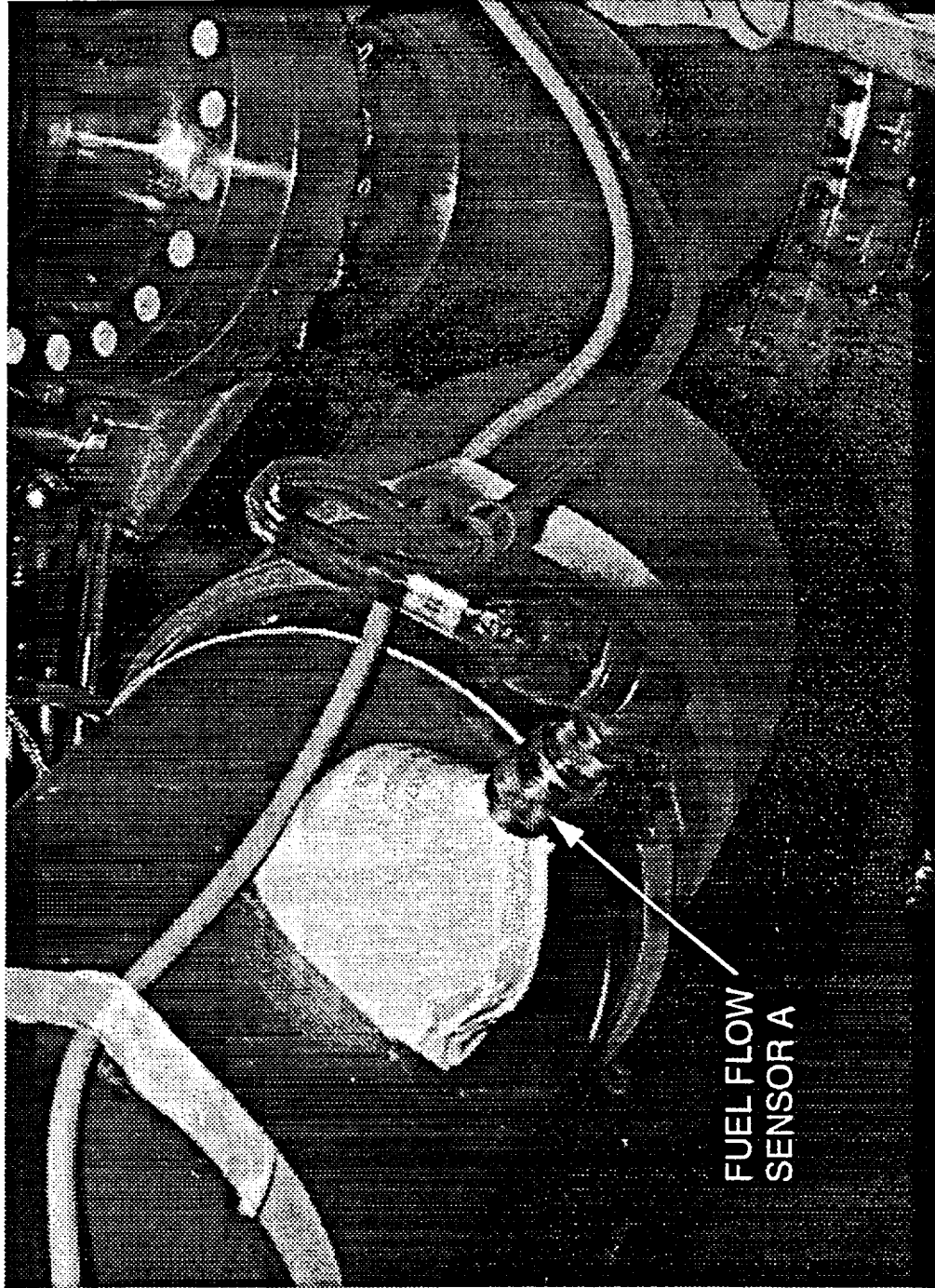


# SSME SCHEMATIC





## STS-51 PAD ABORT ME-2 (ENGINE 2033) FUEL FLOW SENSOR



- NON INTRUSIVE

- MOLDDED  
RTV

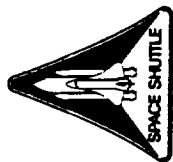
- 2 halves  
+ straps

- MIN 1/2 IN  
THICK

- CHILL DRIVEN  
BY BOILING  
LH<sub>2</sub>@ 40R



- steady state 140 TO 235°R MAX  $\Delta T = 400^\circ$
- EQUILIBRIUM IN 1 hr



# FUEL FLOW MEASUREMENT

## LAYOUT AND PRINCIPLE OF OPERATION

KF1cF Pu#1  
P156

CHANNEL  
"B"

B1, B2  
PRC PRC

LOOKING IN DIRECTION OF FLOW

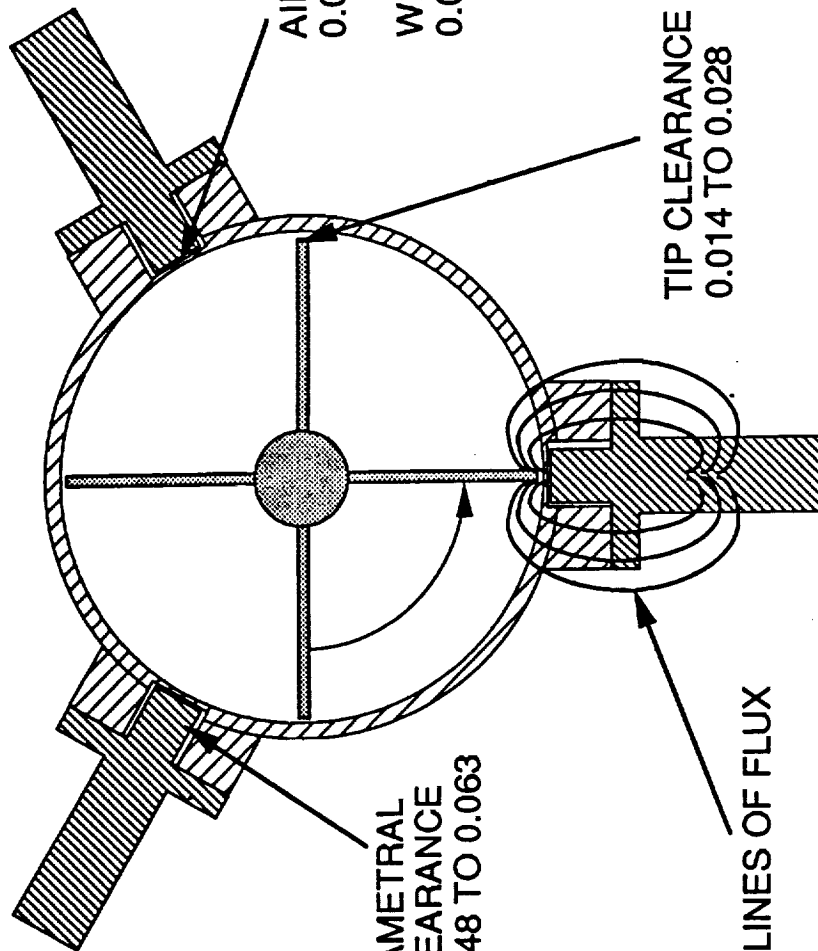
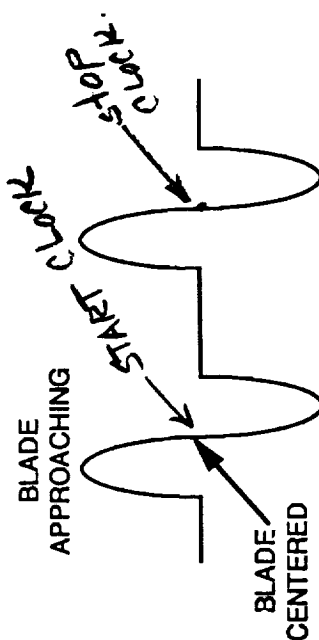
KF1bF Pu#2

P147

CHANNEL  
"A"

A1, A2  
PRC PRC

OUTPUT PULSES

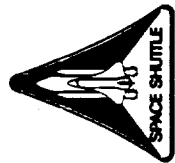


GROUND TEST CHANNEL NFD-1

KF1aF

-2  
FLOW-LAYOUT

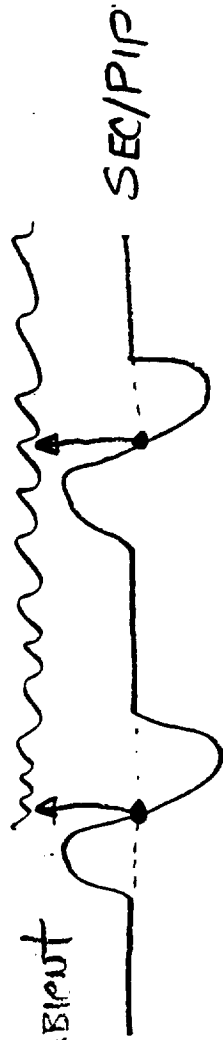




# FUEL FLOW SENSOR CHECKOUT

ΔT

Pre FLT checkout @ Ambient



500 Hz  
CALIBRATION INPUT  
LOCATED ON  
IE3 CARD

PULSE  
RATE  
CONVERTER  
LOCATED ON  
IE3 CARD

COMPUTER  
MEMORY

PULSE  
RATE  
CONVERTER  
LOCATED ON  
IE3 CARD

COMPUTER  
MEMORY

Clock Frequen  
cycles/sec

$$Q = \frac{333333}{S} \times K$$

S = PRC counter  
cycles/PIP

$$\frac{\text{cycles/sec}}{\text{cycles/PIP}} \times K \frac{\text{GAL-SEC}}{\text{PIP-MIN}} = \text{GPM}$$

SENSOR A2

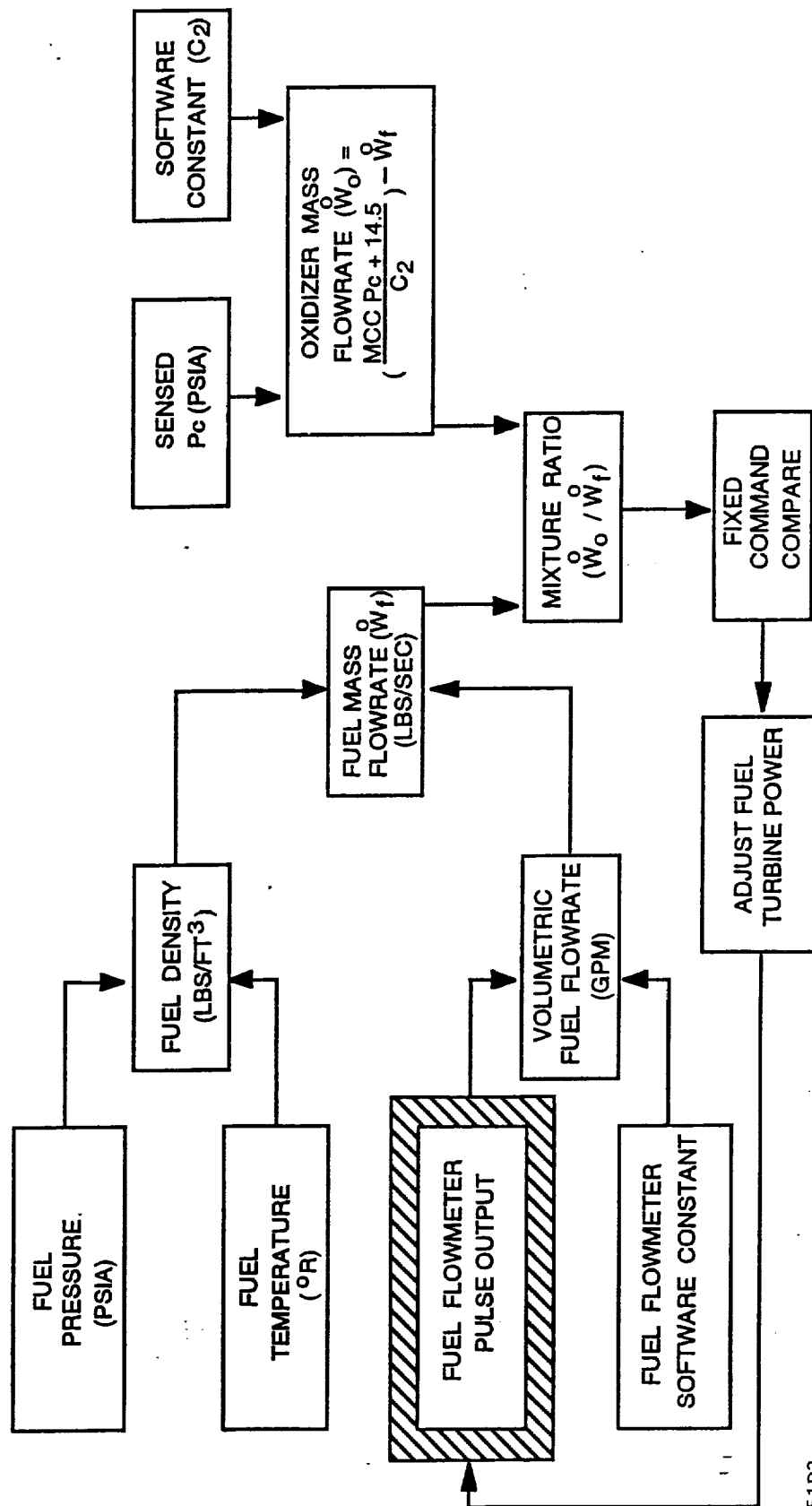
SENSOR A1

FFCKOUT.DRW

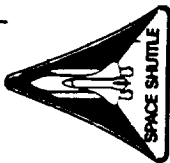




# SSME MIXTURE RATIO CONTROL



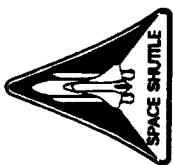
MAC\51D2  
BU



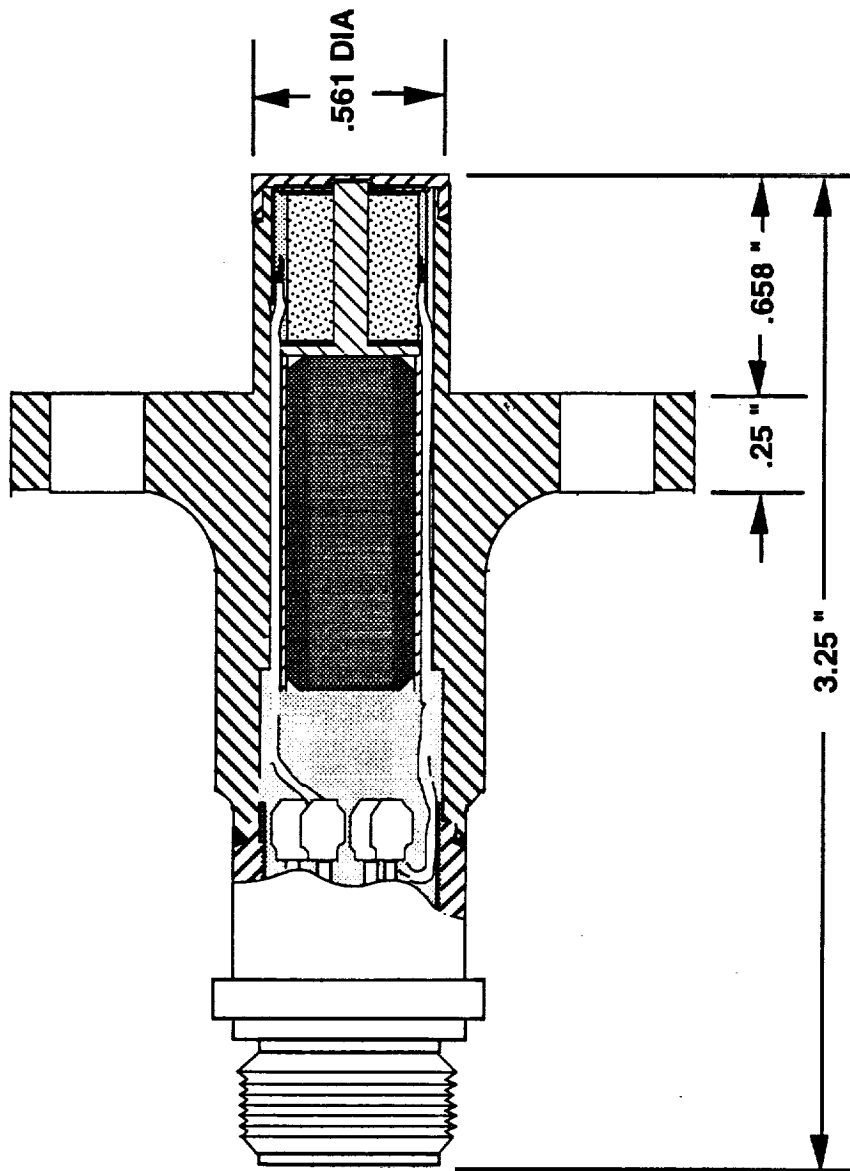
## FLOW SENSOR SOFTWARE LOGIC

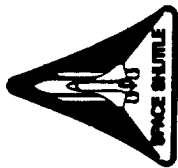
### COMPARISON LIMITS:

- [A1-A2] ≤ 1800 GPM, [B1-B2] ≤ 1800 GPM, CONTINUOUS *INTRA channel check*
- [Aavg-Bavg] ≤ 1800 GPM, 3.5 SECONDS TO MECO *inter channel check*
- REASONABLENESS LIMITS: 3.5 SECONDS TO MECO
- 5,000 GPM MIN & 20,000 GPM MAX *104% 15,700 GPM*
- SHUTDOWN PRIOR TO T-ZERO FOR ANY FAILURE
- DISQUALIFY INDIVIDUAL COILS AFTER T-ZERO *use Remaining coils*
- CONTROL ELECTRICAL LOCKUP FOR LOSS OF ~~BOHEPATES~~ *Three coils*

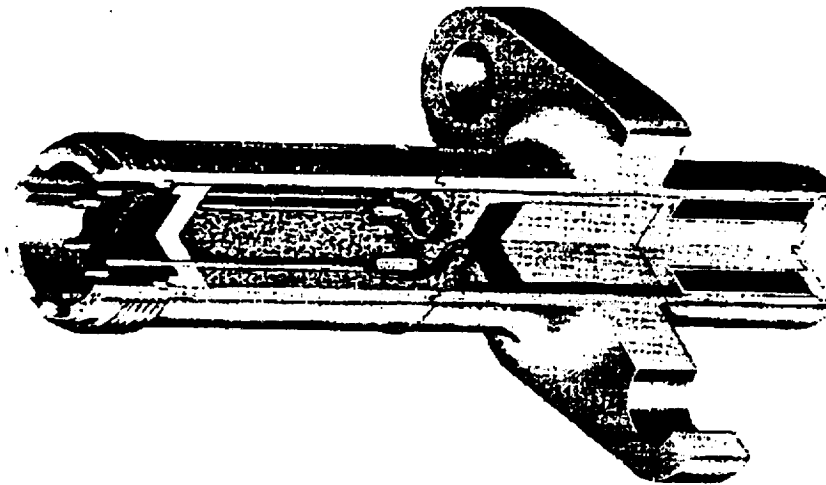


# FUEL FLOW SENSOR RES7005-061 CUTAWAY

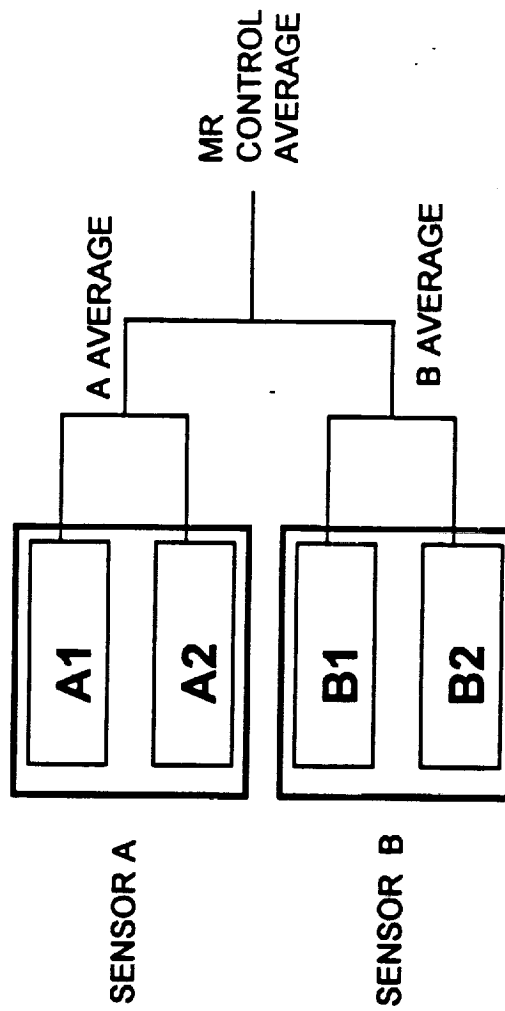




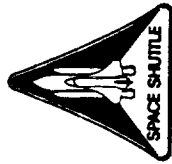
# FUEL FLOW SENSOR



FOUR FUEL FLOW COILS PER ENGINE



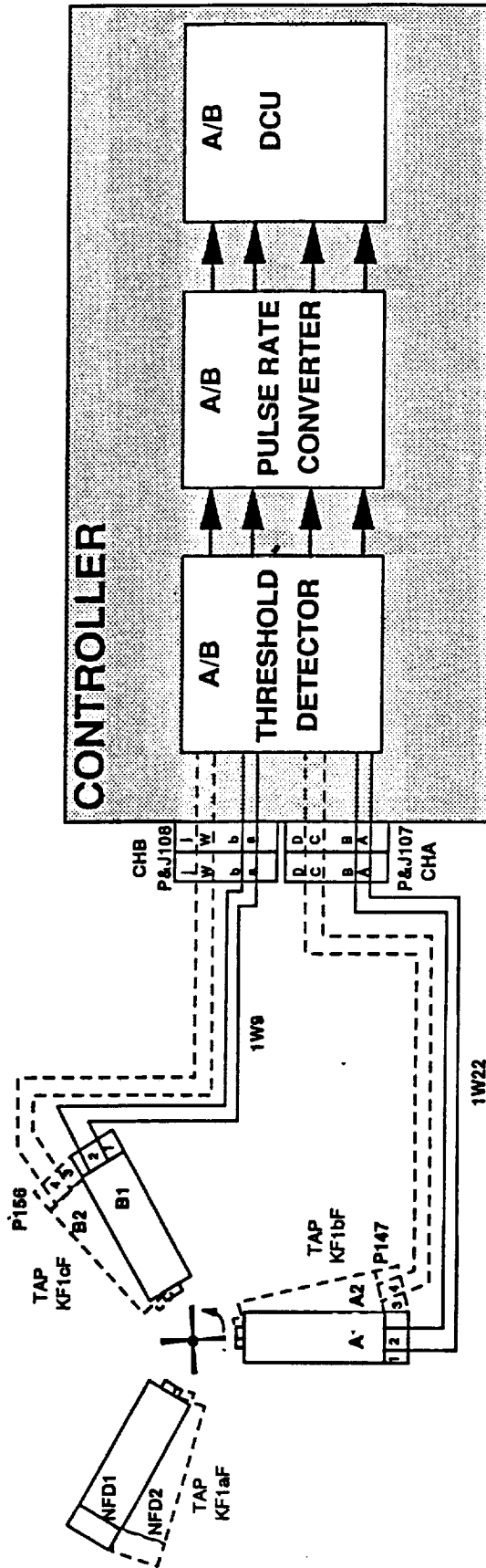
2 FUEL FLOW SENSORS PER ENGINE



# FUEL FLOW CIRCUIT BLOCK DIAGRAM

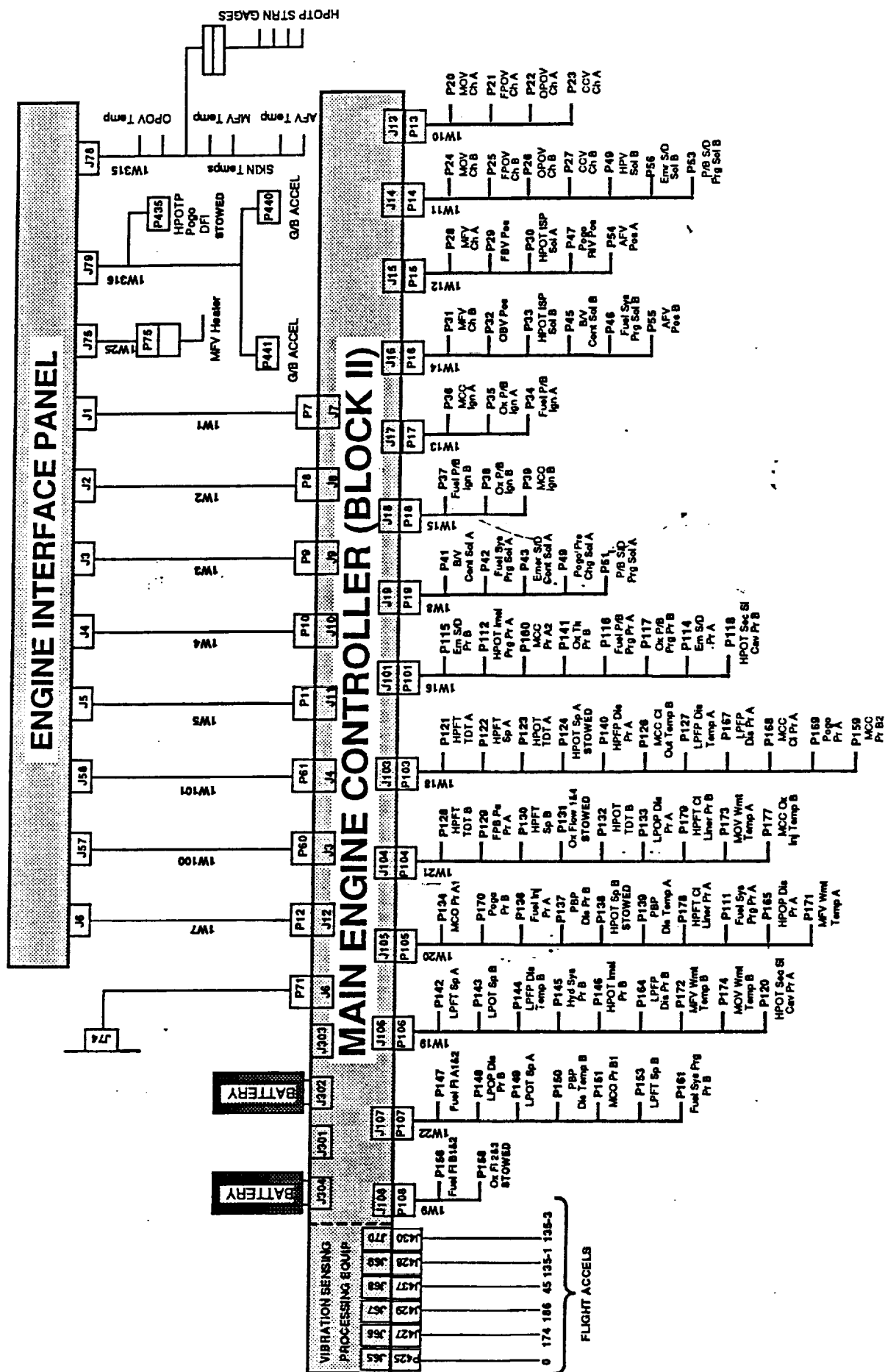
AUGUST 17, 1993

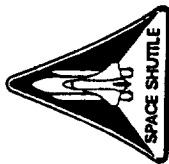
## FUEL FLOW METER



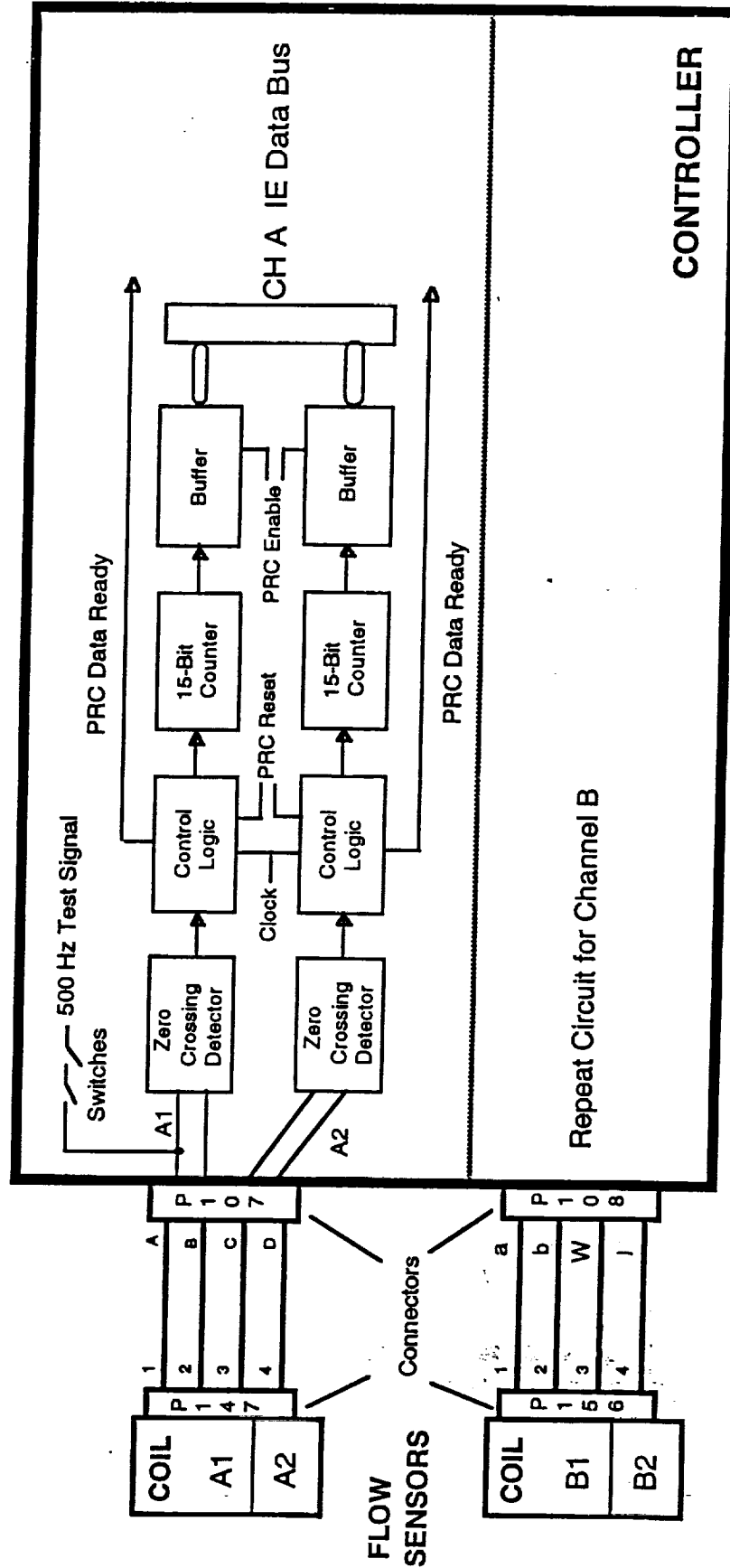
F\_FAULT1.DRW







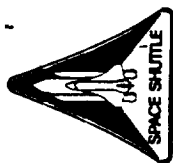
# SENSING SYSTEM





# FUEL FLOW SENSOR CHECKOUT

DETERMINE INTEGRITY OF BOTH SENSOR CIRCUITS ON EACH CHANNEL



- INSERT 500 Hz CALIBRATION SIGNAL INTO ONE SENSOR CIRCUIT ON EACH CHANNEL
- PRC UPDATES FOR EACH SENSOR WITH CORRECT VALUE
- NO PRC UPDATES WHEN SIGNAL REMOVED

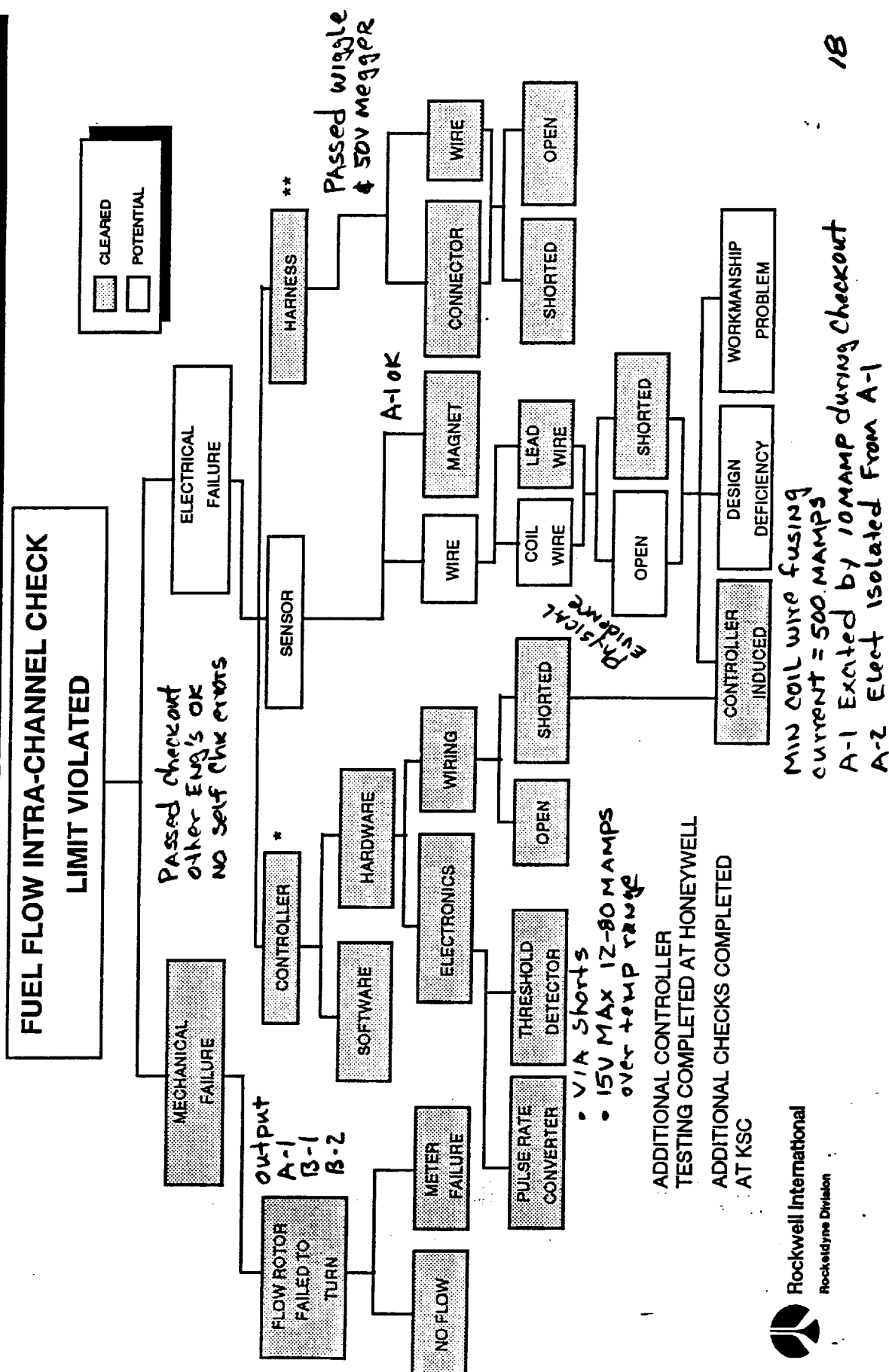
<u>DATE</u>	<u>EVENT</u>	<u>RESULTS</u>
6-27-93	PAD CHECKOUT	NO FAILURES
7-16-93	PRE-LAUNCH SCRUB 1	NO FAILURES
7-23-93	PRE-LAUNCH SCRUB 2	NO FAILURES
8-11-93	PRE-LAUNCH ABORT	NO FAILURES
8-13-93	POST-ABORT	NO FAILURES

	<u>DETECTABLE</u>		<u>COMMENTS</u>
	<u>YES</u>	<u>NO</u>	
• CONTINUITY LOSS ON "HIGH SIDE"	X		
• CONTINUITY LOSS ON "LOW SIDE"		X	MAY OPERATE NORMALLY
• TEMPERATURE DEPENDANT FAILURES		X	



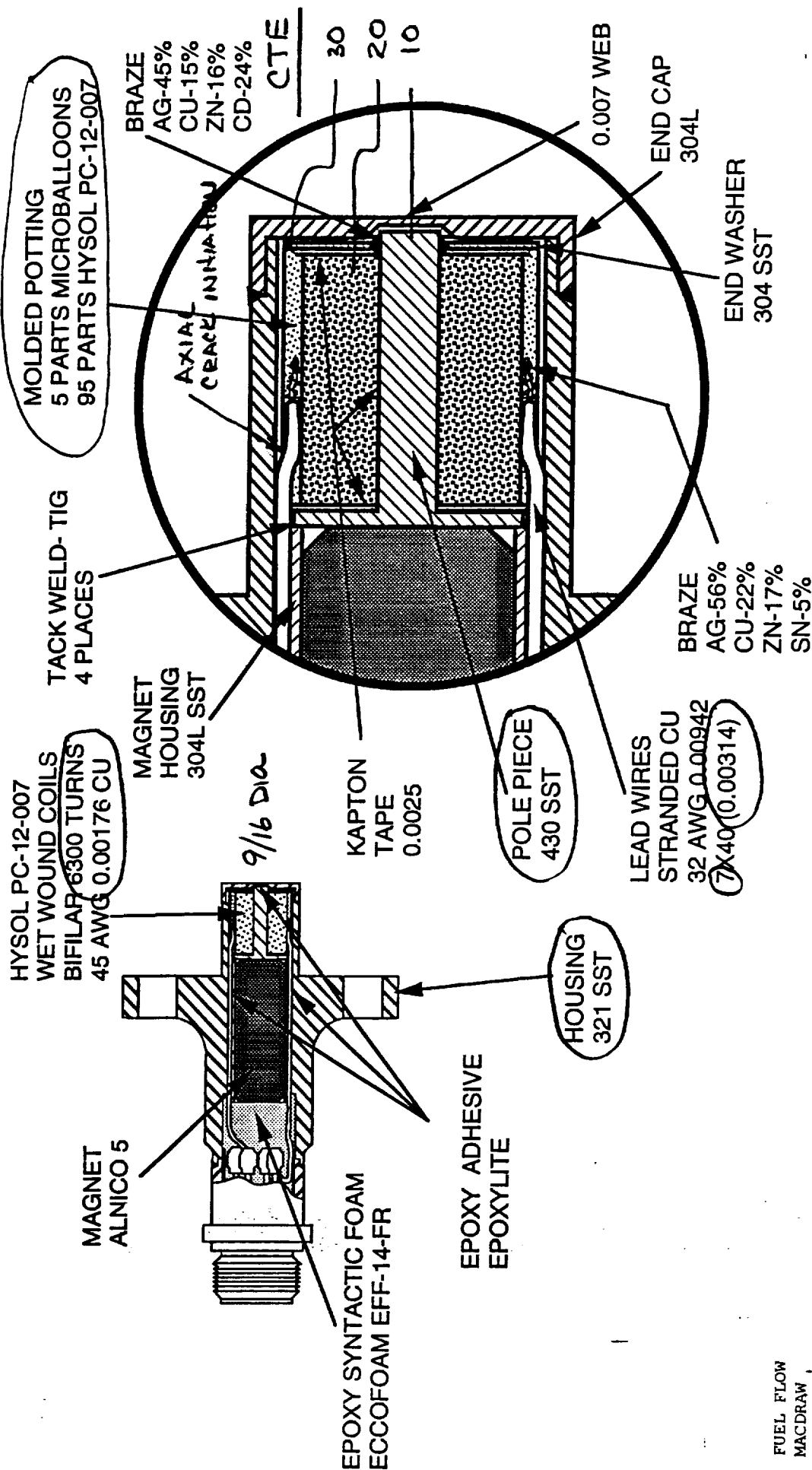
F-42 55+ / 1044 sec

- 2 FLTS STS 52, 56
- Ground Test 201L A-2 FAILURE
- IE FAILURE

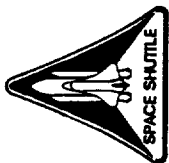


# FUEL FLOW SENSOR CUTAWAY

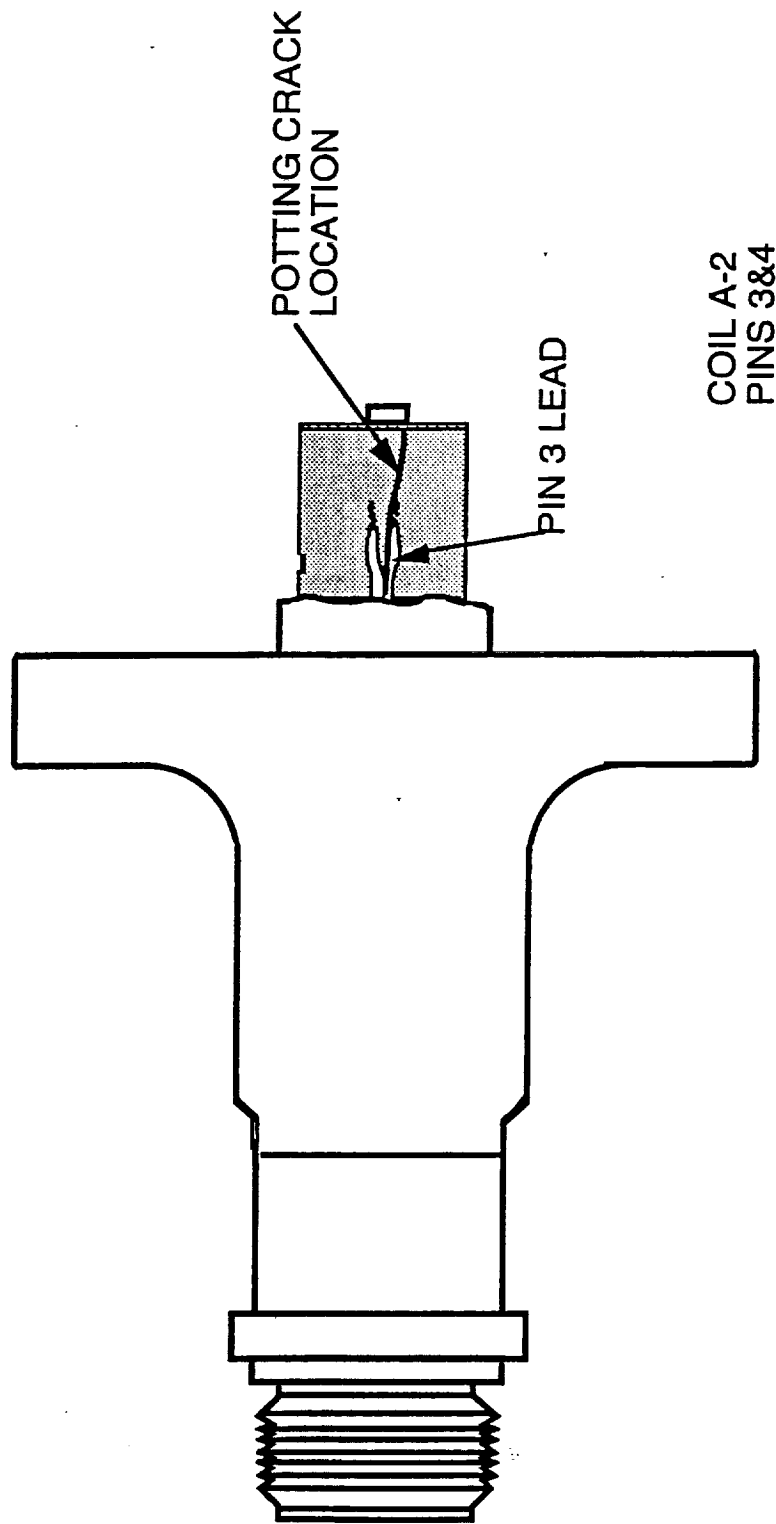
3 1/4 in length



19

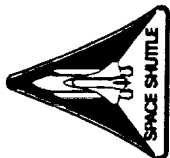


## STS-51A FUEL FLOW SENSOR

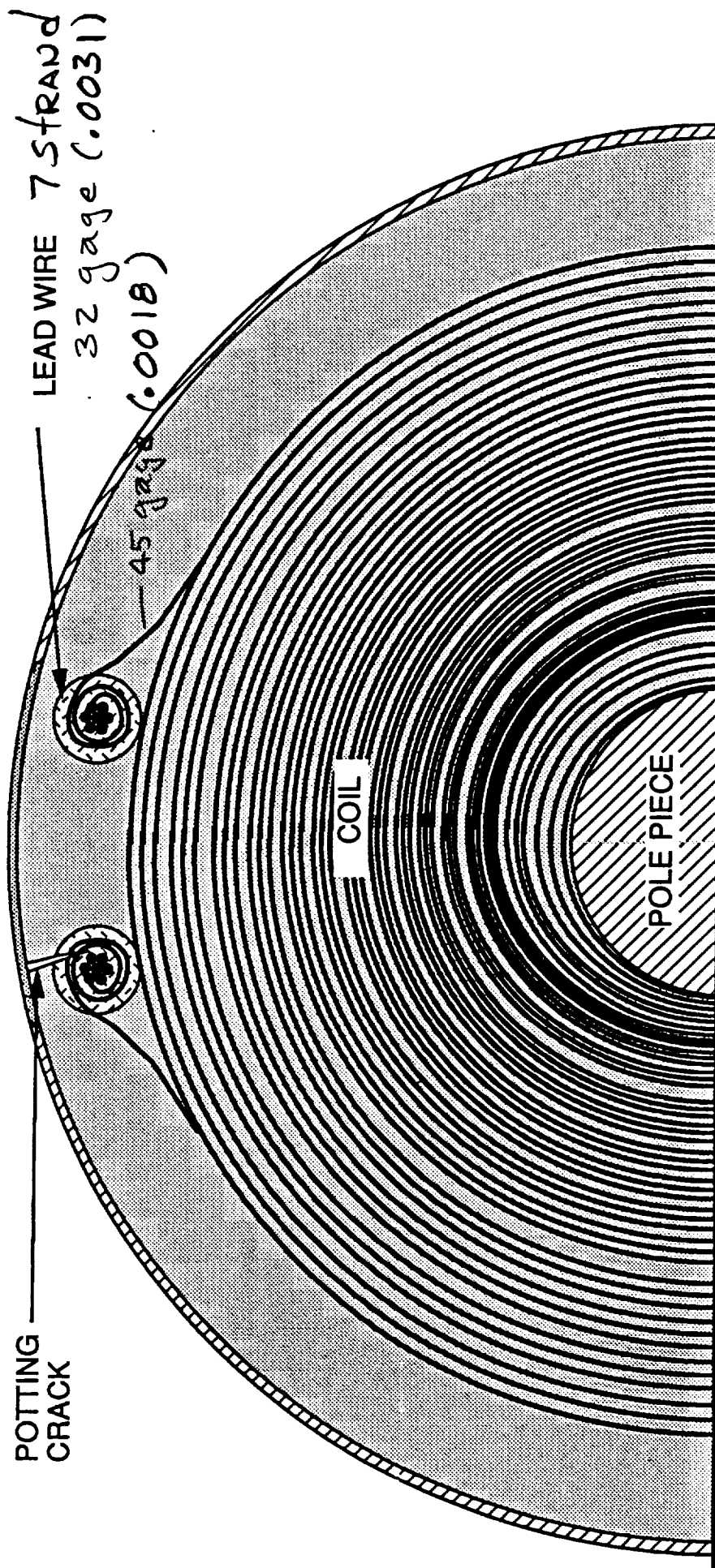


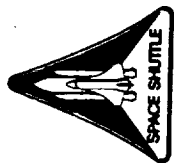
# STS-51A FUEL FLOW SENSOR

## LOCATION OF FAILURE



8/20/93 14:00 HRS

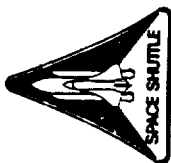




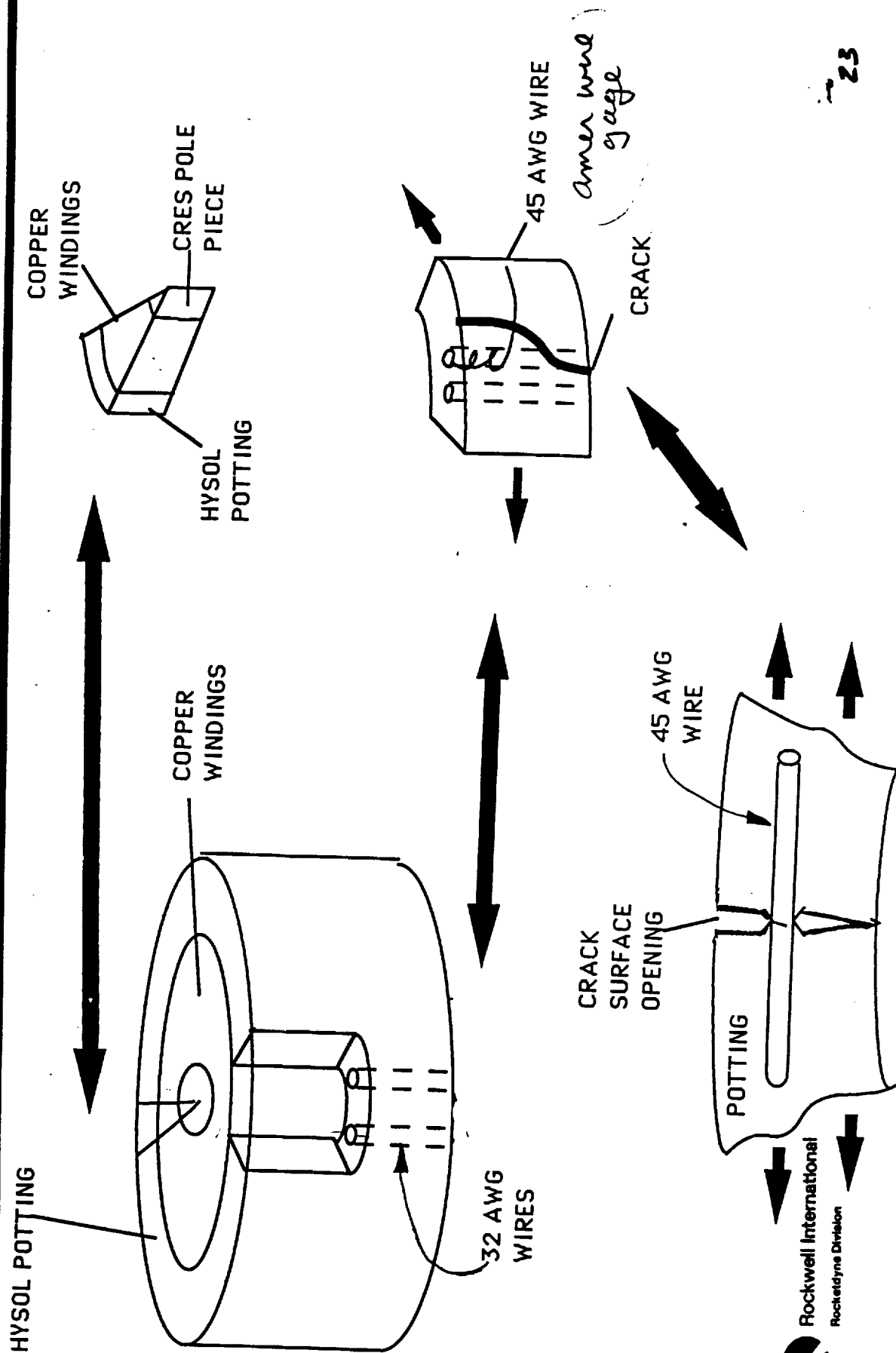
## FAILURE MECHANISM

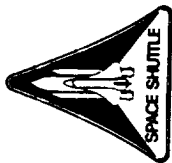
- THERMAL EXPANSION COEFFICIENT MISMATCH BETWEEN THE WINDING COMPOSITE AND THE OUTER POTTING LAYER PRODUCES HIGH TENSILE STRESSES IN THE POTTING
- STRESS CONCENTRATION AT THE INSULATED LEAD WIRE IN THE POTTING MATERIAL INCREASES STRESS CAUSING FAILURE IN THE OUTBOARD LIGAMENT
- CRACK EXTENDS OR PROGRESSES CYCLICALLY ALONG THE WIRE
- IF THE CRACK INTERSECTS THE COIL WIRE, WIRE DOES NOT HAVE SUFFICIENT STRENGTH TO PREVENT POTTING MATERIAL SEPARATION
- IF THE WIRE DOES NOT DEBOND (HIGH SHEAR STRENGTH BETWEEN WIRE AND EPOXY), IT SEVERS
- BOTH ANALYSIS AND HARDWARE SHOW GOOD BOND

	$\frac{CTE}{9}$	$\frac{FTu}{10}$
wire	30	3
Hysol	20	6
coil	10	30



# FUEL FLOW SENSOR FAILURE MECHANISM



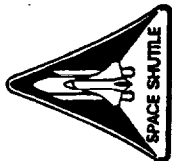


# FAILURE SCENARIO

EVENTS	DATA
(1) FUEL FLOW SENSOR POTTING CRACK INITIATED DUE TO CRYO CHILLING	<ul style="list-style-type: none"> <li>• POTTING MATERIAL SUSCEPTABLE TO CRACKING UNDER CRYOGENIC TEMPERATURES</li> <li>• POTTING CRACKING FOUND IN FAILED UNITS</li> </ul>
(2) CRACK GROWTH AFTER REPEATED CRYO CYCLES CAUSED COIL WIRE TO BREAK BUT UNDETECTED DURING SENSOR CHECKOUT (AMBIENT) OR CRYO LOADING	<ul style="list-style-type: none"> <li>• 7 SUCCESSFUL HOT-FIRES INCLUDING 3 FLIGHTS PRIOR TO FAILURE</li> <li>• 3 SENSOR CHECKOUTS @ AMBIENT CONDITIONS PRIOR TO ABORT SHOWED NO ANOMALIES</li> <li>• NO DETECTION METHOD DURING PRELAUNCH CRYO LOADING SEQUENCE</li> <li>• POST ABORT SENSOR CHECKOUT SHOWED NO ANOMALIES (AMBIENT)</li> </ul>
(3) UNDETECTED OPEN COIL WIRE CAUSED MISCOMPARE AND ENGINE SHUTDOWN	<ul style="list-style-type: none"> <li>• FAILURE DUPLICATED AT VENDOR UNDER CRYO CONDITIONS (LN2) - RECOVERY @ 57°F</li> <li>• TEARDOWN INSPECTION INDICATED CRACKED POTTING</li> <li>• CONFIRMED COIL WIRE BREAK IN 2ND STRAIN RELIEF WINDING AT LEAD WIRE- DUCTILE FRACTURE</li> </ul>

51SCENAR.TBL





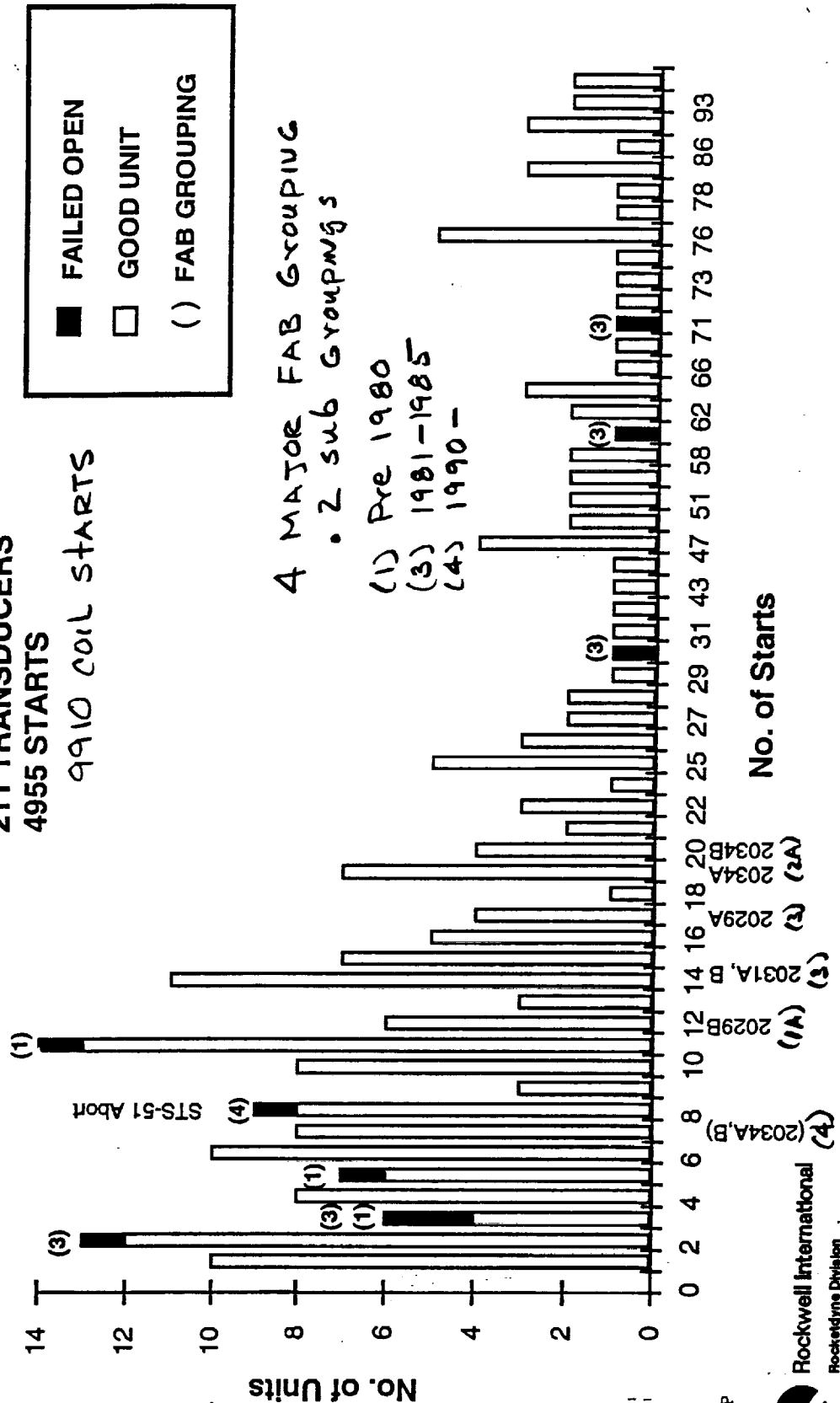
# FUEL FLOW SENSOR FAILURE HISTORY

FUEL FLOW SENSOR OPEN CIRCUIT FAILURES DUE TO CRACKED POTTING					
S/N	HOT FIRE		HOT FIRE DATE	PHASE DETECTED	ANALYSIS
	STARTS	SECONDS			
905	11	2713	06-79	POST SHUTDOWN	OPEN @ AMBIENT
1399	5	159	10-79	93 SECONDS	OPEN @ AMBIENT
1474	3	352	09-80	PRESTART	OPEN @ AMBIENT
2010	3	772	12-87	10 SECONDS	OPEN @ AMBIENT
2211	2	532	08-89	PRESTART	FAIL LN <sub>2</sub> TEST
1969	71	12897	10-90	CHECKOUT	OPEN @ AMBIENT
2186	61	25847	02-91	PRESTART	OPEN @ AMBIENT
2004	30	14438	07-92	START	FAIL LN <sub>2</sub> TEST
2583	8	2437	08-93 (STS-51A)	START	FAIL LN <sub>2</sub> TEST



Bu-4

211 TRANSDUCERS  
4955 STARTS  
9910 COIL STARTS



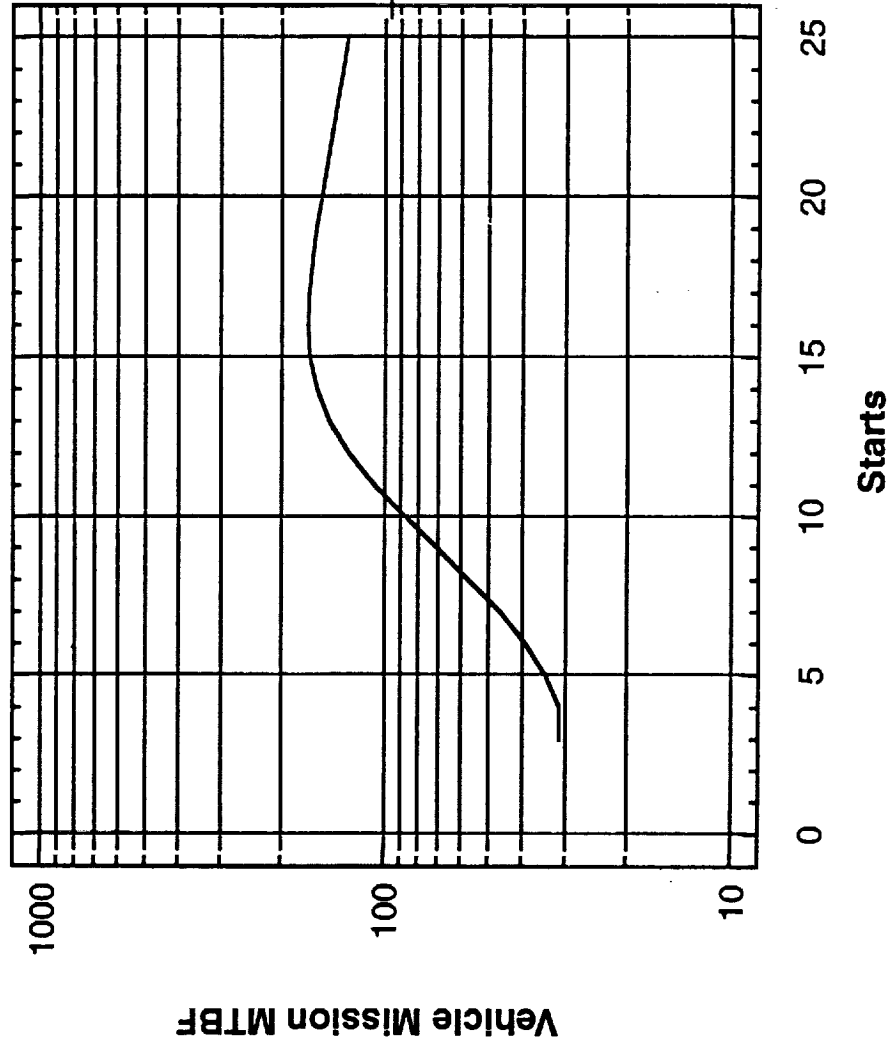
MAC\51D2  
J601E1.PP

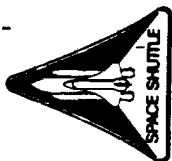


**Rockwell International**  
**Rocketdyne Division**



# FUEL FLOW SENSOR MTBF VS STARTS



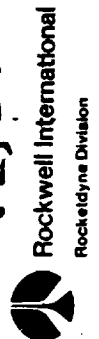


# FLOW SENSOR GROUPINGS

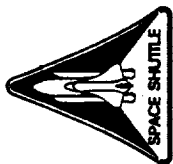
GROUP	HOT-FIRED UNITS	TOTAL STARTS	LN <sub>2</sub>		THERMAL		CYCLES		VIBRATION SCREEN	FAILURES
			NUMBER	TYPE	TYPE	LEVEL				
1	34	720	5	RAPID		FINAL		NO		3 < 11 STARTS
1A	42	1653	+5	SLOW	30 MINUTES	FINAL		YES		NONE
2	04	14	5/5	SLOW		COIL/FINAL		NO		NONE
2A	27	757	+5	SLOW		FINAL		YES		NONE
3	70	1270	10/5	SLOW		COIL/ATP		YES		5 < 572
4*	9	58	10/5	SLOW		COIL/ATP		YES		1 < 8

\* NOTE: 5 YEAR PRODUCTION GAP SINCE GROUP 3  
MAX STARTS PRIOR TO FAILURE -7

- 1, 1A Pre 1980 FAB, 1A 12/81-5/82 screen
- 2, 2A 1980, 2A 12/81-3/83 screen



• 3 82 Thru 85 FAB  
• 4 90 FAB

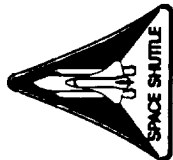


# STS-51 SENSORS

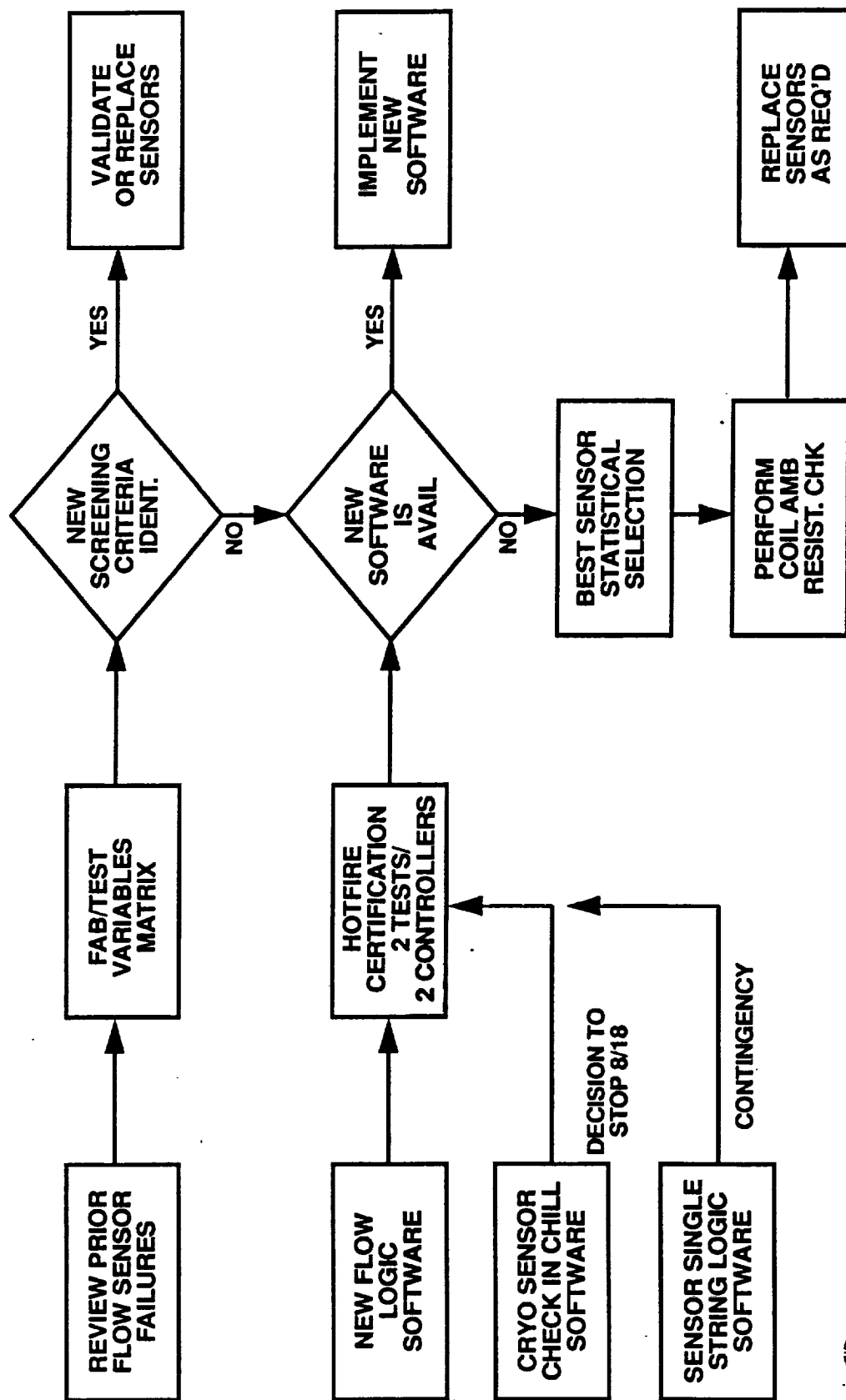
ENGINE	CHANNEL	SERIAL NUMBER	GROUP	TOTAL STARTS
2031	A	2525	3	14
	B	2524	3	14
2034	A	2602	4	7
	B	2598	4	7
2029	A	2520	3	17
	B	1329	1A	12
2034 REPLACEMENT SENSORS	A	1624	2A	19
	B	1689	2A	20



Rockwell International  
Rocketdyne Division

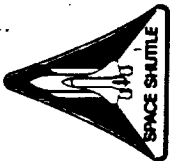


# STS-51 SUPPORT LOGIC



BU-6  
-7

81DEXEP81



## FUEL FLOW SOFTWARE LOGIC CHANGE

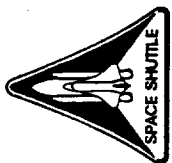
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- ALLOWS LAUNCH WITH ONE FLOW SENSOR COIL FAILURE
- BY ADDING A FLOW REFERENCE (Qref) MODEL
- DERIVED FROM MIXTURE RATIO CONTROL LOOP EQUATIONS

$$W_{F_{\text{COMMANDED}}} = \frac{P_C + 14.5}{C_2} \times \frac{1}{1 + MR_{\text{COMMANDED}}}$$

$$Q_{\text{REF}} = \frac{W_{F_{\text{COMMANDED}}}(448.8)}{\text{DENSITY}}$$

- INDIVIDUAL CHANNEL COMPARED TO Qref
  - LESS THAN 3600 GPM FROM 3.5 TO 5.0 SECONDS
  - LESS THAN 1800 GPM FROM 5.0 SECONDS TO CUTOFF
- HIGHER START LIMIT COMPENSATION FOR START VARIATIONS



# FUEL FLOW SENSOR CHECK SOFTWARE

## LOGIC CHANGE

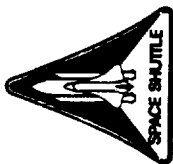
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- ALLOW LAUNCH WITH ONE FLOW COIL SENSING SYSTEM FAILURE
- EACH CHANNEL VALIDATED BY COMPARISON TO REFERENCE FLOW CALCULATION
  - LESS THAN 1800 GPM PRESTART AND FROM 5.0 SECONDS TO CUTOFF
  - LESS THAN 3600 GPM FROM 3.5 TO 5.0 SECONDS (START VARIATIONS)
- $Q_{REF}$  DERIVED FROM MIXTURE RATIO CONTROL LOOP EQUATIONS

**MR COMMAND = 6.011**

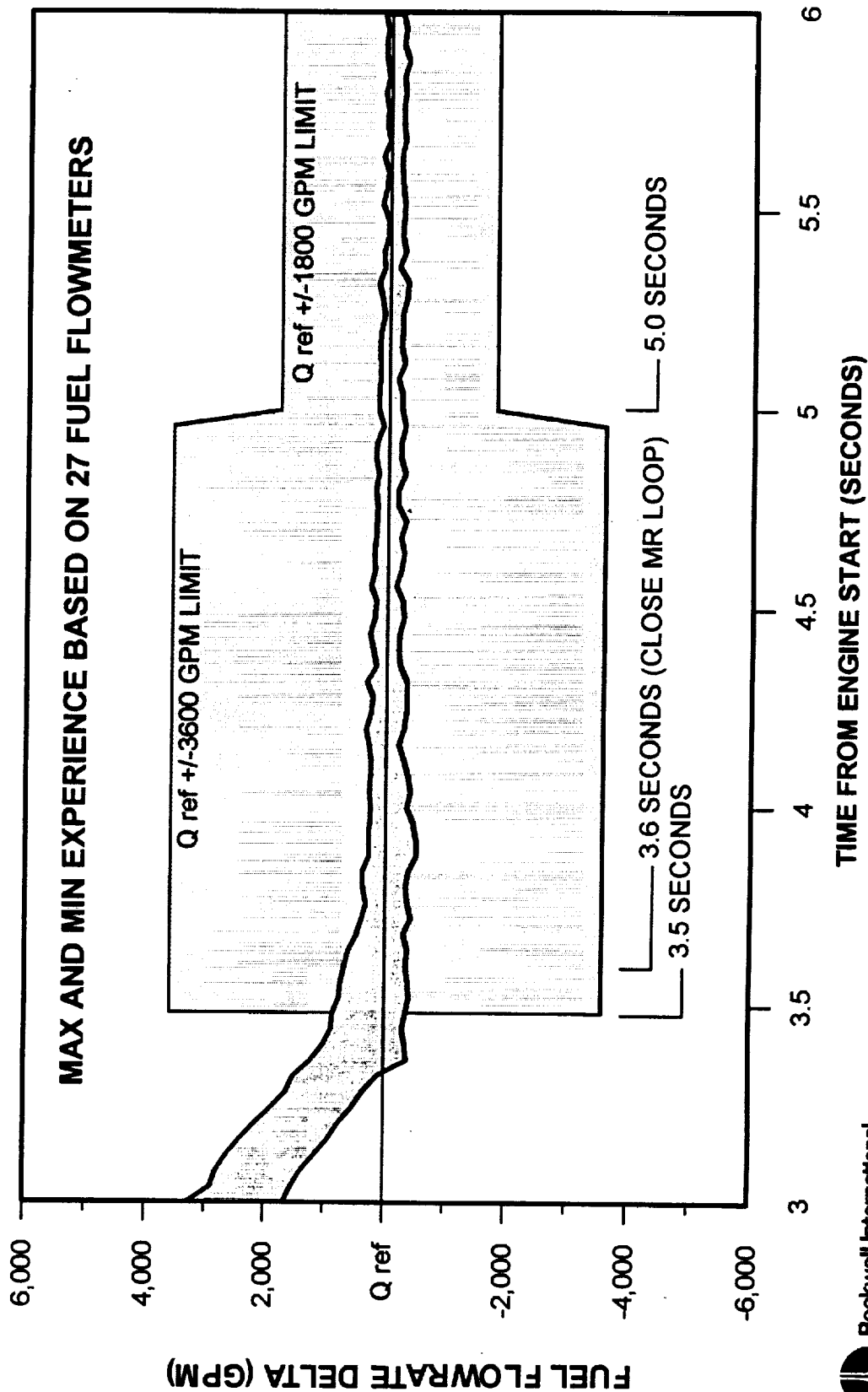
$$Q_{REF} = \frac{P_C + K_1}{K_2 \times DENSITY}$$

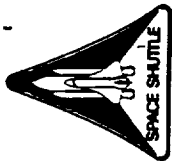




# FUEL FLOW DATABASE

## PROPOSED REASONABLENESS LIMITS





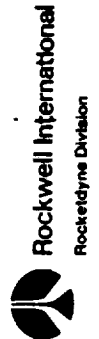
# FUEL FLOW FAILURE RESPONSES BY SOFTWARE OPTIONS

## RECOMMEND OPTION (3)

FAILURE	(1) OI-5	(2) OI-5 SINGLE STRING	(3) OI-5 WITH FLOW SENSOR CHANGE	(4) SOFTWARE OPTION TO OPERATE ON ONE COIL
SENSOR A1 IN START	<ul style="list-style-type: none"> <li>DISQUAL. A1, A2</li> <li>MCF</li> <li>SHUTDOWN BY ORBITER</li> </ul>	<ul style="list-style-type: none"> <li>DISQUAL. A1, A2</li> <li>LAUNCH WITH B1, B2 ACTIVE</li> </ul>	<ul style="list-style-type: none"> <li>DISQUAL. A1</li> <li>LAUNCH WITH A2, B1, B2 ACTIVE</li> </ul>	<ul style="list-style-type: none"> <li>DISQUAL. A1</li> <li>LAUNCH WITH A2, B1, B2 ACTIVE</li> </ul>
SENSOR A1 IN START A2 IN MS	N/A	NO EFFECT	<ul style="list-style-type: none"> <li>DISQUAL. A2</li> <li>CONTINUE B1, B2</li> </ul>	<ul style="list-style-type: none"> <li>DISQUAL. A2</li> <li>CONTINUE B1, B2</li> </ul>
SENSOR A1 IN START SENSOR B1 IN MS	N/A	<ul style="list-style-type: none"> <li>DISQUAL. B1, B2</li> <li>ELECT. LOCKUP</li> </ul>	<ul style="list-style-type: none"> <li>DISQUAL. B1</li> <li>CONTINUE A2, B2</li> </ul>	<ul style="list-style-type: none"> <li>DISQUAL. B1</li> <li>CONTINUE A2, B2</li> </ul>
SENSOR A1 IN START IE-A IN MS	N/A	NO EFFECT	<ul style="list-style-type: none"> <li>DISQUAL. A2</li> <li>CONTINUE B1, B2</li> </ul>	<ul style="list-style-type: none"> <li>DISQUAL. A2</li> <li>CONTINUE B1, B2</li> </ul>
SENSOR A1 IN START IE-B IN MS	N/A	<ul style="list-style-type: none"> <li>DISQUAL. B1, B2</li> <li>ELECT. LOCKUP</li> </ul>	<ul style="list-style-type: none"> <li>DISQUAL. B1, B2</li> <li>ELECT. LOCKUP</li> </ul>	<ul style="list-style-type: none"> <li>DISQUAL. B1, B2</li> <li>CONTINUE A2</li> </ul>

operate on one coil

1 IN 179K FLT'S



# FUEL FLOWRATE MONITOR

## QUALIFICATION

### OI-5 AA24

MONITOR PERIOD		MONITOR DESCRIPTION	RESPONSE	ENGINE STATUS WORD
BEGIN	END			
CHECK OUT (1)	—	<ul style="list-style-type: none"> <li>FUEL FLOWRATE INTRA-CHANNEL TEST</li> <li>• <math> A1-A2 ,  B1-B2  &lt; 1800 \text{ GPM}</math></li> </ul>	1ST FAILURE- • DISQUALIFY, INHIBIT 2ND FAILURE- • DISQUALIFY, INHIBIT, REJECT PSN1-4 COMMANDS	MCF MCF-NR
PSN1	E/S	<ul style="list-style-type: none"> <li>FUEL FLOWRATE INTRA-CHANNEL TEST</li> <li>• <math> A1-A2 ,  B1-B2  &lt; 1800 \text{ GPM}</math></li> </ul>	1ST FAILURE- • DISQUALIFY, INHIBIT 2ND FAILURE- • DISQUALIFY, REJECT PSN1-4 COMMANDS, PNEU S/D	MCF MCF-NR
E/S	E/S +3.48 SEC	<ul style="list-style-type: none"> <li>PULSE RATE CONVERTER UPDATE TEST (P.L.&gt;49%)</li> <li>• PRC MUST UPDATE EVERY MAJOR CYCLE (A1,A2,B1,B2)</li> </ul>	1ST,2ND FAILURE- • DISQUALIFY 3RD FAILURE- • DISQUALIFY • SHUTDOWN (START) OR ELECTRICAL LOCKUP (M/S) 4TH FAILURE- • DISQUALIFY	MCF MCF-NR MCF-NR
E/S +3.50 SEC	S/D	<ul style="list-style-type: none"> <li>FUEL FLOWRATE INTRA-CHANNEL TEST</li> <li>• <math> A1-A2 ,  B1-B2  &lt; 1800 \text{ GPM}</math></li> </ul>	1ST FAILURE- • DISQUALIFY 2ND FAILURE- • DISQUALIFY • SHUTDOWN (START) OR ELECTRICAL LOCKUP (M/S)	MCF MCF-NR
E/S +3.50 SEC	S/D	<ul style="list-style-type: none"> <li>PULSE RATE CONVERTER UPDATE TEST (P.L.&gt;49%)</li> <li>• PRC MUST UPDATE EVERY MAJOR CYCLE (A1,A2,B1,B2)</li> <li>FUEL FLOWRATE REASONABLENESS TEST</li> <li>• <math>5,000 &lt; A1,A2,B1,B2 &lt; 20,000 \text{ GPM}</math></li> </ul>	1ST,2ND FAILURE- • DISQUALIFY 3RD FAILURE- • DISQUALIFY • SHUTDOWN (START) OR ELECTRICAL LOCKUP (M/S) 4TH FAILURE- • DISQUALIFY	MCF MCF-NR MCF-NR
		<ul style="list-style-type: none"> <li>FUEL FLOWRATE INTER-CHANNEL TEST</li> <li>• <math> A \text{ AVG} - B \text{ AVG}  &lt; 1800 \text{ GPM}</math></li> <li>FUEL FLOWRATE INTRA-CHANNEL TEST</li> <li>• <math> A1-A2 ,  B1-B2  &lt; 1800 \text{ GPM}</math></li> </ul>	1ST FAILURE- • DISQUALIFY 2ND FAILURE- • DISQUALIFY • SHUTDOWN (START) OR ELECTRICAL LOCKUP (M/S)	MCF MCF-NR
S/D	POST S/D	<ul style="list-style-type: none"> <li>PULSE RATE CONVERTER UPDATE TEST (P.L.&gt;49%)</li> <li>• PRC MUST UPDATE EVERY MAJOR CYCLE (A1,A2,B1,B2)</li> </ul>	1ST,2ND FAILURE- • DISQUALIFY 3RD FAILURE- • DISQUALIFY 4TH FAILURE- • DISQUALIFY	MCF MCF-NR MCF-NR
		<ul style="list-style-type: none"> <li>FUEL FLOWRATE INTRA-CHANNEL TEST</li> <li>• <math> A1-A2 ,  B1-B2  &lt; 1800 \text{ GPM}</math></li> </ul>	1ST FAILURE- • DISQUALIFY 2ND FAILURE- • DISQUALIFY	MCF MCF-NR
POST S/D	—	<ul style="list-style-type: none"> <li>FUEL FLOWRATE INTRA-CHANNEL TEST</li> <li>• <math> A1-A2 ,  B1-B2  &lt; 1800 \text{ GPM}</math></li> </ul>	1ST FAILURE- • DISQUALIFY 2ND FAILURE- • DISQUALIFY	MCF MCF-NR

(1) NOT ACTIVE DURING SENSOR CHECKOUT OR CONTROLLER CHECKOUT  
 • INTRA-CHANNEL TEST FAILURE REQUIRES 3 CONSECUTIVE PRC UPDATED STRIKES  
 • PRC, REASONABLENESS TESTS FAILURE REQUIRE 3 CONSECUTIVE MAJOR CYCLE STRIKES

FFRQUALM.TBL

**FUEL FLOW RATE METER (OI-5 AA24)**

PHASE	CHECKOUT	START PREPARATION	START	MAINSTAGE	SHUTDOWN	POST SHUTDOWN
MODE	EXCLUDES SENSOR AND CONTROLLER CHECKOUT	<ul style="list-style-type: none"> <li>PSN1</li> <li>PSN2</li> <li>PSN3</li> <li>PSN4</li> <li>ENGINE READY</li> </ul>	<ul style="list-style-type: none"> <li>START INITIATION</li> <li>THRUST BUILDUP</li> <li>FIXED DENSITY</li> </ul>	<ul style="list-style-type: none"> <li>NORMAL CONTROL</li> <li>THRUST LIMITING</li> <li>HYDRAULIC LOCKUP</li> <li>ELECTRICAL LOCKUP</li> <li>FIXED DENSITY</li> </ul>	<ul style="list-style-type: none"> <li>THROTTLE TO 0</li> <li>PROP VALVES CLOSED</li> <li>FAIL SAFE PNEUMATIC</li> </ul>	<ul style="list-style-type: none"> <li>STAND-BY</li> <li>OXIDIZER DUMP</li> <li>TERMINATE SEQUENCE</li> </ul>
TIMES						
EVENTS						

0.00' 5.00'

3.60 (CLOSED LOOP MIXTURE RATIO CONTROL)

3.50 (BEGIN FLOWRATE QUALIFICATION MONITOR)

2.40 (INTEGRAL Pc CONTROL)

0.74 (PROPORTIONAL Pc CONTROL)

3.00 (PL > 49% RPL)

**PULSE RATE CONVERTER UPDATE TEST (P.L. > 49%)**  
 PRC MUST UPDATE EVERY MAJOR CYCLE

- 1ST, 2ND FAILURE (MCF)
- 3RD FAILURE (MCF-NR)
- 4TH FAILURE (MCF-NR)

**SENSOR REASONABLENESS TEST**  
 5,000 < A1, A2, B1, B2 < 20,000 GPM

- 1ST, 2ND FAILURE (MCF)
- 3RD FAILURE (MCF-NR)
- 4TH FAILURE (MCF-NR)

**INTER-CHANNEL TEST**  
 | A - B AVERAGE | < 1800 GPM

- 1ST FAILURE (MCF-NR)

**INTRA-CHANNEL TEST**  
 | A1 - A2 |, | B1 - B2 | < 1800 GPM

- 1ST FAILURE (MCF)
- 2ND FAILURE (MCF-NR)

# FUEL FLOWRATE MONITOR QUALIFICATION OI-5 AA35

MONITOR PERIOD		MONITOR DESCRIPTION	RESPONSE	ENGINE STATUS WORD
BEGIN	END			
CHECK OUT	—	• NONE		
PSN1 (1)	E/S	<ul style="list-style-type: none"> <li>• FUEL FLOWRATE QUALIFICATION TEST</li> <li>• 0 &lt; (A1,A2,B1,B2)-Qref &lt; 1800 GPM</li> </ul>	1ST FAILURE- DISQUALIFY 2ND FAILURE- DISQUALIFY, INHIBIT 3RD FAILURE- DISQUALIFY, REJECT PSN1-4 COMMANDS, PNEU S/D 4TH FAILURE- DISQUALIFY	--- MCF MCF-NR MCF-NR
E/S	E/S +3.48 SEC	<ul style="list-style-type: none"> <li>• PULSE RATE CONVERTER UPDATE TEST (P.L.&gt;49%)</li> <li>• PRC MUST UPDATE EVERY MAJOR CYCLE (A1,A2,B1,B2)</li> </ul>	1ST FAILURE- DISQUALIFY 2ND FAILURE- DISQUALIFY	--- MCF
E/S +3.50 SEC	M/S	<ul style="list-style-type: none"> <li>• PULSE RATE CONVERTER UPDATE TEST (P.L.&gt;49%)</li> <li>• PRC MUST UPDATE EVERY MAJOR CYCLE (A1,A2,B1,B2)</li> <li>• FUEL FLOWRATE QUALIFICATION TEST</li> <li>• 0 &lt; (A1,A2,B1,B2)-Qref &lt; 3600 GPM</li> </ul>	3RD FAILURE- DISQUALIFY, SHUTDOWN 4TH FAILURE- DISQUALIFY	MCF-NR MCF-NR
M/S	S/D	<ul style="list-style-type: none"> <li>• PULSE RATE CONVERTER UPDATE TEST (P.L.&gt;49%)</li> <li>• PRC MUST UPDATE EVERY MAJOR CYCLE (A1,A2,B1,B2)</li> <li>• FUEL FLOWRATE QUALIFICATION TEST</li> <li>• 0 &lt; (A1,A2,B1,B2)-Qref &lt; 1800 GPM</li> </ul>	1ST FAILURE- DISQUALIFY 2ND FAILURE- DISQUALIFY 3RD FAILURE- DISQUALIFY, ELECTRICAL LOCKUP 4TH FAILURE- DISQUALIFY	--- MCF MCF-NR MCF-NR
S/D	POST S/D	<ul style="list-style-type: none"> <li>• PULSE RATE CONVERTER UPDATE TEST (P.L.&gt;49%)</li> <li>• PRC MUST UPDATE EVERY MAJOR CYCLE (A1,A2,B1,B2)</li> </ul>	1ST FAILURE- DISQUALIFY 2ND FAILURE- DISQUALIFY 3RD FAILURE- DISQUALIFY 4TH FAILURE- DISQUALIFY	--- MCF MCF-NR MCF-NR
POST S/D	—	<ul style="list-style-type: none"> <li>• FUEL FLOWRATE QUALIFICATION TEST</li> <li>• 0 &lt; (A1,A2,B1,B2)-Qref &lt; 1800 GPM</li> </ul>	1ST FAILURE- DISQUALIFY 2ND FAILURE- DISQUALIFY 3RD FAILURE- DISQUALIFY, REJECT PSN1-4 COMMANDS, PNEU S/D 4TH FAILURE- DISQUALIFY	--- MCF MCF-NR MCF-NR

(1) • FUEL FLOWRATE QUALIFICATION TEST FAILURE REQUIRES 3 CONSECUTIVE PRC UPDATED STRIKES  
 • PRC UPDATE TEST FAILURE REQUIRES 3 CONSECUTIVE MAJOR CYCLE STRIKES

FFRQUAL.1.TBL

# FUEL FLOW RATE MONITOR (OI-5 AA35)

PHASE	CHECKOUT	START PREPARATION	START	MAINSTAGE	SHUTDOWN	POST SHUTDOWN
MODE	NONE	<ul style="list-style-type: none"> <li>PSN1</li> <li>PSN2</li> <li>PSN3</li> <li>PSN4</li> <li>ENGINE READY</li> </ul>	<ul style="list-style-type: none"> <li>START INITIATION</li> <li>THRUST BUILDUP</li> <li>FIXED DENSITY</li> </ul>	<ul style="list-style-type: none"> <li>NORMAL CONTROL</li> <li>THRUST LIMITING</li> <li>HYDRAULIC LOCKUP</li> <li>ELECTRICAL LOCKUP</li> <li>FIXED DENSITY</li> </ul>	<ul style="list-style-type: none"> <li>THROTTLE TO 0</li> <li>PROP VALVES CLOSED</li> <li>FAIL SAFE PNEUMATIC</li> </ul>	<ul style="list-style-type: none"> <li>STAND-BY</li> <li>OXIDIZER DUMP</li> <li>TERMINATE SEQUENCE</li> </ul>

0.00' 5.00'

0.74 (PROPORTIONAL Pc CONTROL)

2.40 (INTEGRAL Pc CONTROL)

3.50 (BEGIN FLOWRATE QUALIFICATION MONITOR)

3.60 (CLOSED LOOP MIXTURE RATIO CONTROL)

3.00 (PL > 49% RPL)

PULSE RATE CONVERTER UPDATE TEST (P.L. > 49%)

PRC MUST UPDATE EVERY MAJOR CYCLE

- 1ST FAILURE
- 2ND FAILURE (MCF)
- 3RD FAILURE (MCF-NR)
- 4TH FAILURE (MCF-NR)

FUEL FLOWRATE QUALIFICATION TEST

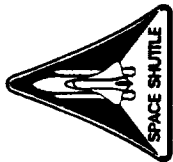
0 < (A1,A2,B1,B2)-Qref < 1800 GPM

- 1ST FAILURE
- 2ND FAILURE (MCF)
- 3RD FAILURE (MCF-NR)
- 4TH FAILURE (MCF-NR)

FUEL FLOWRATE QUALIFICATION TEST

0 < (A1,A2,B1,B2)-Qref < 3600 GPM

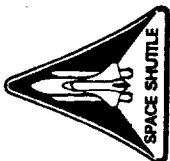
- 1ST FAILURE
- 2ND FAILURE (MCF)
- 3RD FAILURE (MCF-NR)
- 4TH FAILURE (MCF-NR)



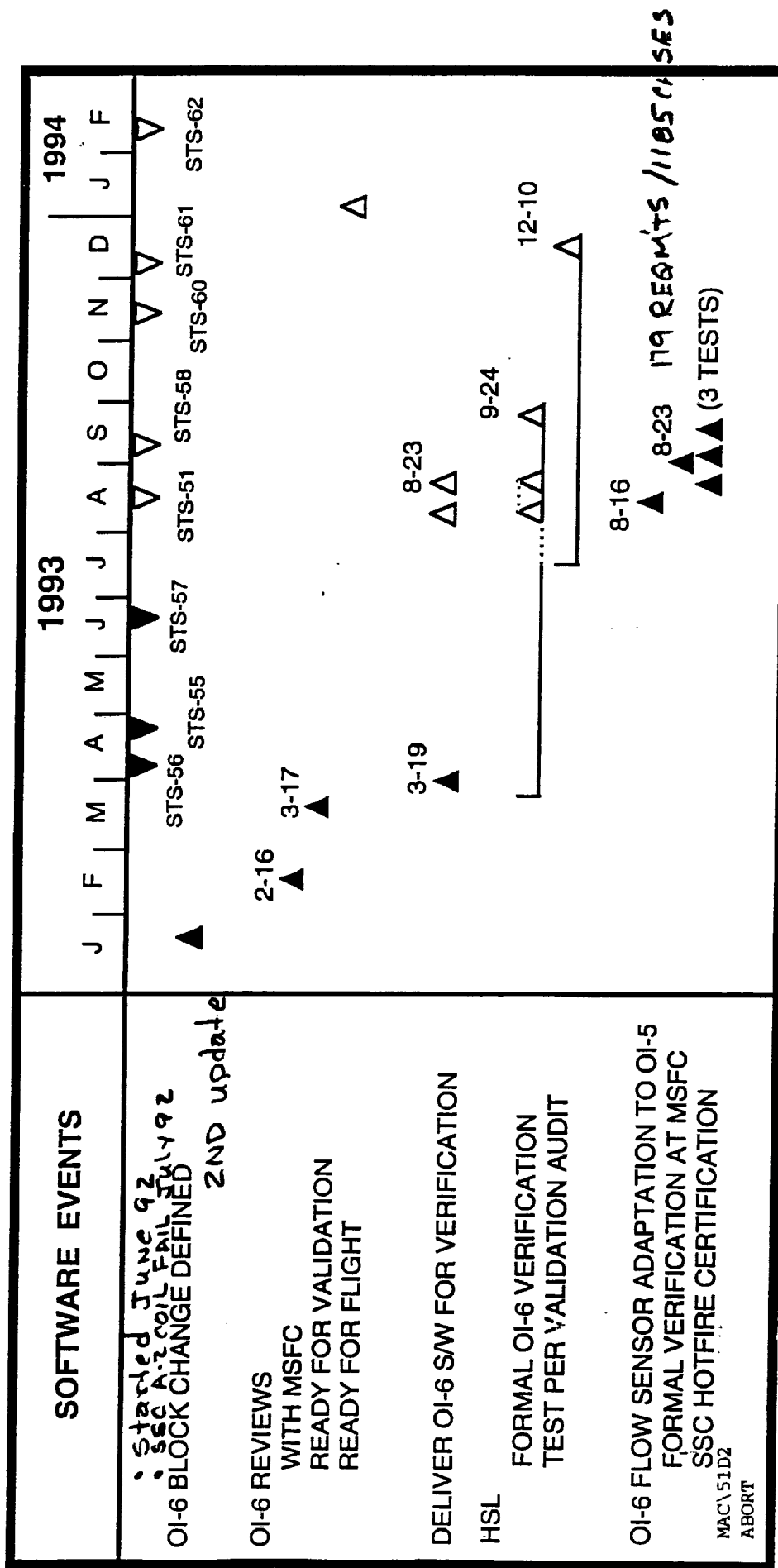
## **FUEL FLOW LOGIC SOFTWARE VERIFICATION**

---

- PREVIOUSLY VERIFIED AS PART OF OI-6 SOFTWARE DESIGN
- ALL OI-5 ASSOCIATED SOFTWARE SPECIFICATION REQUIREMENTS TESTED AND VERIFIED @ HSL (179 TOTAL REQUIREMENTS)
  - 1185 TOTAL TEST CASES RUN
  - INCLUDED ENGINE RESPONSE TO FAILED FUEL FLOW SENSOR(S)
- FUNCTIONAL MODULE LEVEL TESTS CONDUCTED IN COMPLIANCE WITH SOFTWARE AUDIT
- INDEPENDENT ASSESSMENT OF SOFTWARE CHANGE SUCCESSFULLY COMPLETED 8/30/93
  - NASA/ROCKETDYNE/HONEYWELL/SMITH ADVANCE TECHNOLOGY



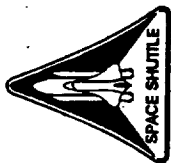
# SSME FLIGHT SOFTWARE CHANGE



INDEPENDENT AUDIT COMPLETED 8/30







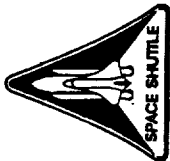
# STS-51 SOFTWARE HOTFIRE CERTIFICATION

TEST (DATE)	ENGINE	CONTROLLER	FLOW SENSOR S/N		DURATION
			CHAN A	CHAN B	
902-583 (8-27-93)	2015	F62	2015	2012	300
904-186 (8-28-93)	0220	F47	2696 *	2519	300
904-187 (8-31-93)	0220	F47	2696 *	2519	125

\* REDESIGN (POTTING) SENSOR

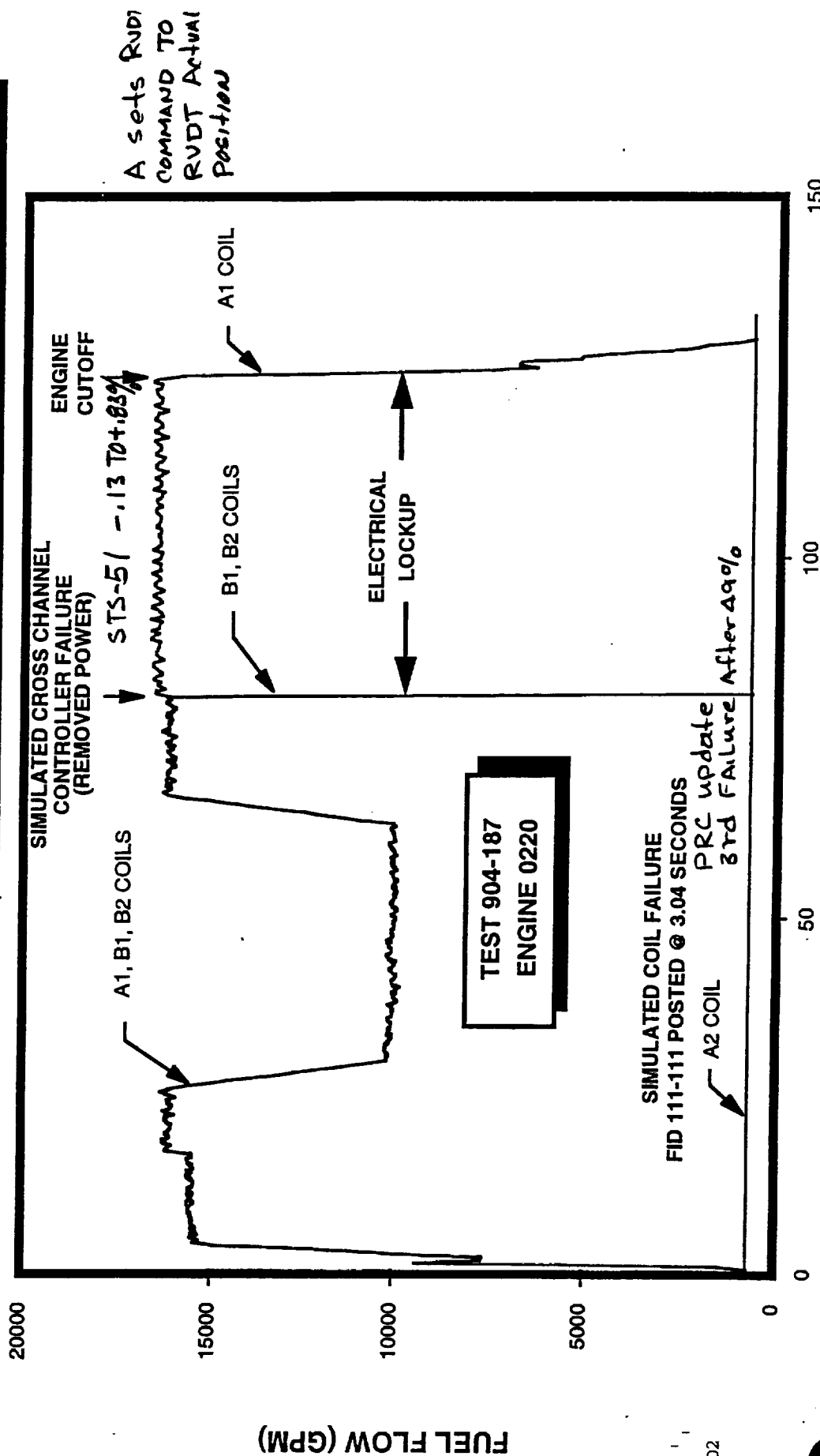
MAC\51D2  
BU

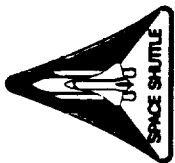




# SOFTWARE VERIFICATION HOT-FIRE

RVDT curve fits biased for end points  
• ensure no leak closed  
• ensure full open





## BLOCK II SOFTWARE VALVE POSITION INITIALIZATION

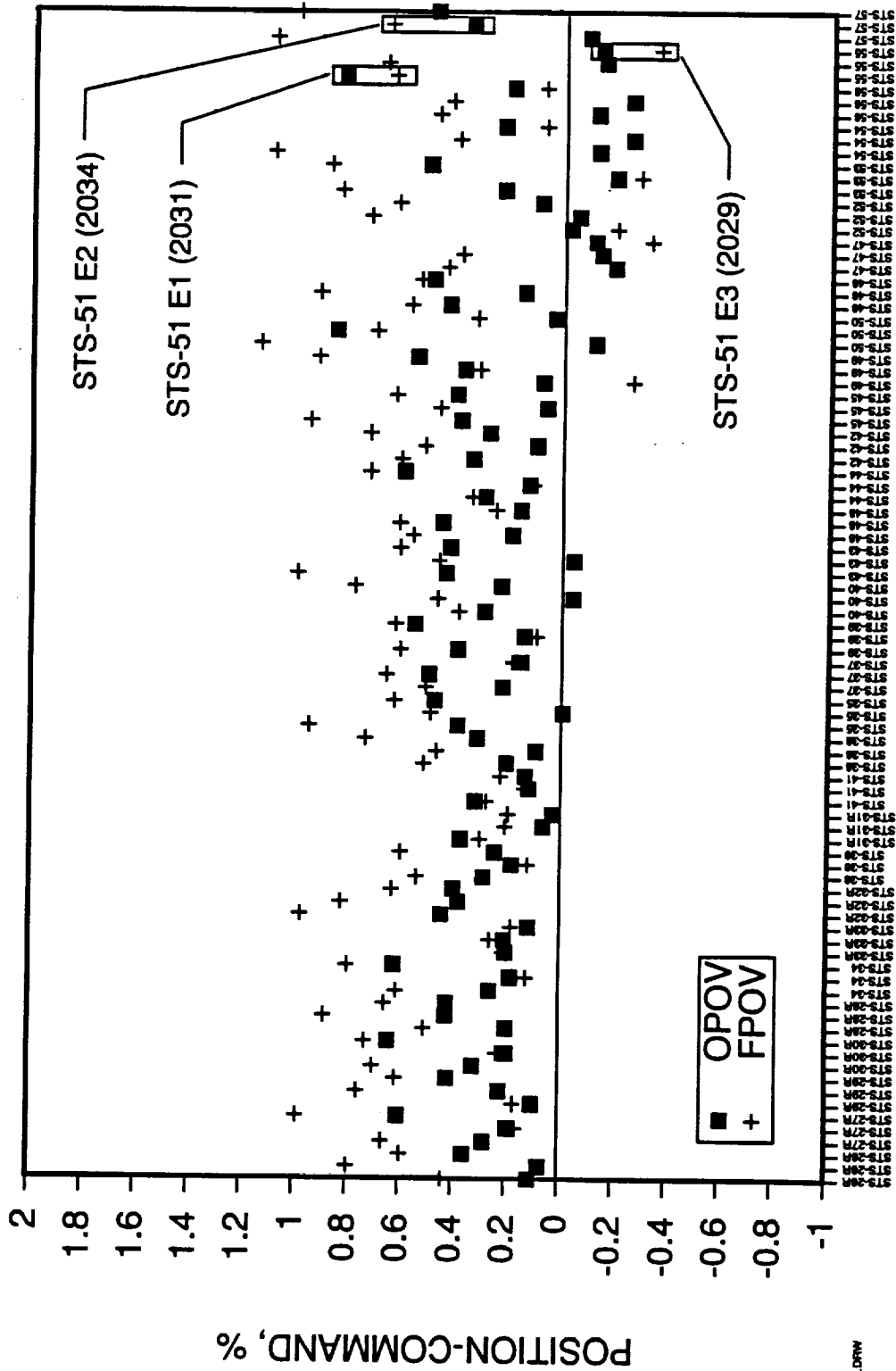
- **ISSUE**
  - OBSERVED A 1% UPWARD SHIFT IN THE OPOV POSITION ON TEST 904-187
- **ANALYSIS**
  - SHIFT OCCURRED AFTER SIMULATED CH B POWER FAILURE
  - COMMAND WAS SET TO THE RVDT POSITION AS REQUIRED PER NORMAL SOFTWARE RESPONSE
  - VALVE OPENED 1% AND WAS MAINTAINED - STANDARD ELECTRICAL LOCKUP REQUIREMENT

SOFTWARE	POWER FAILURE IN		IE FAILURE	
	CH A	CH B	CH A	CH B
BLOCK I	POSITION	POSITION	COMMAND	
BLOCK II (OI-5)	POSITION	POSITION	POSITION	
BLOCK II (OI-6)	POSITION	COMMAND	COMMAND	

- VALVE COMMAND INITIALIZATION COMPARISON



# PREBURNER VALVES COMMAND BIAS POSITION-COMMAND

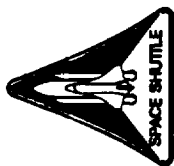


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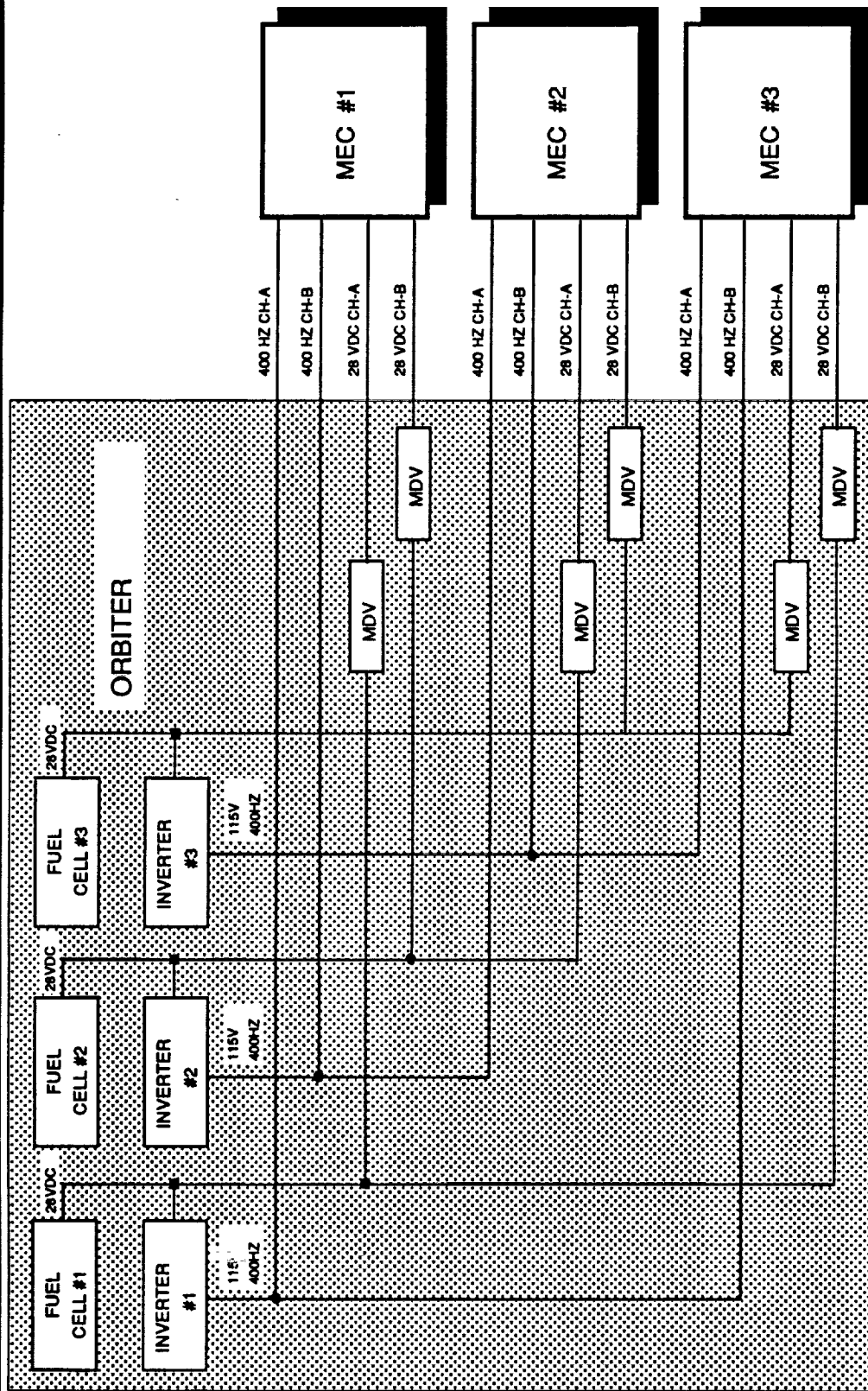


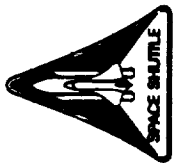
Rockwell International

Rocketdyne Division



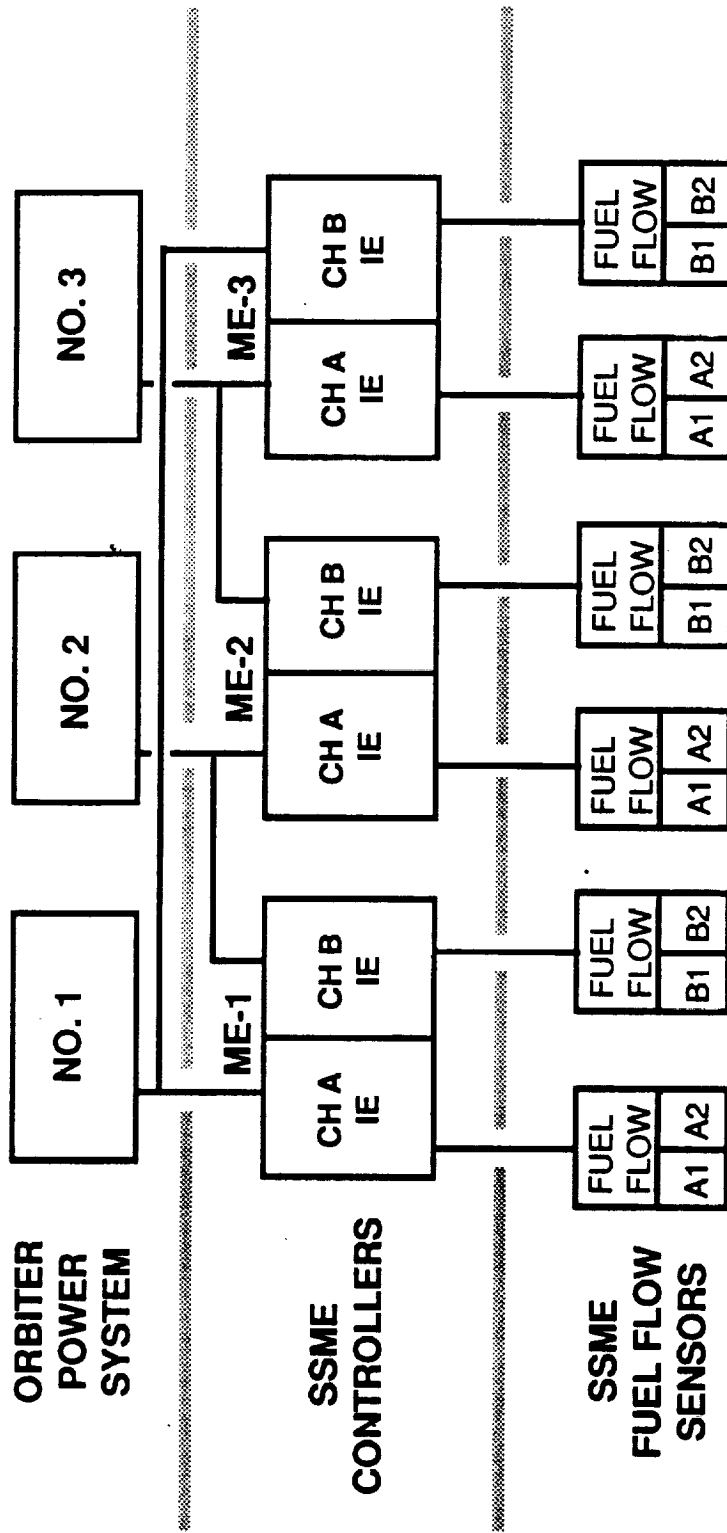
# ELECTRICAL POWER INTERFACE SSME CONTROLLER





# SYSTEM ASSESSMENT

• 28V DC  
• 115V 400Hz



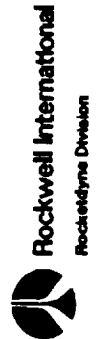
3

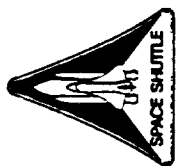
6

12

- ANY 3 ON ONE ENG → Elect Lookup
- ONE power syst. Fail → 2 IE Failures → 4 COIL Failures  
1 IE FAILURE → 2 COIL Failures

MAC\51D2  
ABORT





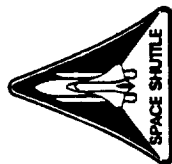
## FLIGHT RULE 5-33

### MANUAL S/D FOR HYD OR ELECTRICAL LOCKUP

08/20/93

- WITH THREE ENGINES ON - ONE STUCK THROTTLE (NOMINAL/ATO/AOA)
  - BEFORE BUCKET AND AFTER BUCKET - ORBIT
  - ABORT REGION DETERMINATOR (ARD) COMPUTER PREDICTS NOMINAL VEHICLE PERFORMANCE AFTER SRB SEPARATION - NO ACTION REQUIRED
  - ARD PREDICTS LOW VEHICLE PERFORMANCE AFTER SRB SEPARATION - STUCK ENGINE WILL BE MANUALLY SHUTDOWN AT INSERTION VELOCITY  $\geq$  23K FPS TO PROTECT FOR LOX NPSP REQUIREMENT
- IN BUCKET
  - RTLS OR TAL (MOST PROBABLE)
  - REDLINE LIMITS INHIBITED BY CREW SWITCH ON OTHER ENGINES (RULE 5-27)

FR\_5-33.WRD



# SSME FAILURE HISTORY DATABASE FOR PROBABILITY CALCULATIONS

COMPONENT	FAILURES	BASE	MTBF	RELIABILITY
FUEL FLOW SENSOR	9	9910 COIL STARTS	1101 COIL STARTS	.9990919
CONTROLLER CHANNEL	1	25,900 HOURS	179,300 FLIGHTS	.9999945
ACTUATORS	1	20000 CHANNEL TESTS	20000 CHANNEL STARTS	.9999500
MCC PC SENSORS	1	1,000,000 BRIDGE SECS	1,000,000 BRIDGE SECS	.9999999

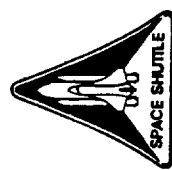
## NOTES:

- 3 ENGINES PER VEHICLE, ONE FLIGHT IS 520 SECONDS
- 4 FUEL FLOW SENSORS PER ENGINE, 2 ON CHANNEL A AND 2 ON CHANNEL B
- 2 CONTROLLER CHANNELS PER ENGINE, 1 CHANNEL A AND 1 CHANNEL B
- 10 ACTUATOR CHANNELS PER ENGINE, 5 ON CHANNEL A AND 5 ON CHANNEL B
- 4 MCC PC SENSORS PER ENGINE, 2 ON CHANNEL A AND 2 ON CHANNEL B



Lockup: SRB SEP NOM Perf - NO ACTION  
 LOW Perf - MANUAL S/D 23K FPS  
 Bucket - ATO

9 FAILURES IN 9910 STARTS  
 $\frac{9910}{9(12)} = 92/\text{veh OR } 276/\text{ENG}$  1101 COIL STARTS



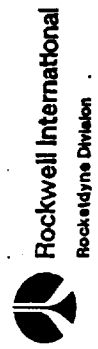
# SOFTWARE INCORPORATION IMPACT FAILURE PROBABILITIES

DATABASE: 9 FAILURES, 9910 STARTS, 2,480,000 SECONDS      620,000 Sec x 4 coils

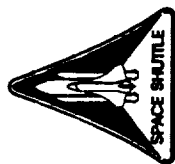
	MTBF	90%
<b>EXISTING OI-5 SOFTWARE</b> <ul style="list-style-type: none"> <li>PAD ABORT (1 OF 12 FAIL)</li> <li>POST LIFTOFF ELECTRICAL LOCKUP (3 OF 4 FAIL)</li> </ul>	92 12M	58 3.1
<b>MODIFIED OI-5 SOFTWARE</b> <ul style="list-style-type: none"> <li>PAD ABORT (2 OF 4 FAIL)</li> <li>POST LIFTOFF ELECTRICAL LOCKUP (1 BEFORE LIFTOFF, 2 OF 3 AFTER LIFTOFF)</li> <li>POST LIFTOFF ELECTRICAL LOCKUP (1 BEFORE LIFTOFF AND CROSS CHANNEL IE)</li> </ul>	67,000 8.6M 16M	27,000 2.2 2.7

M = MILLION

1 EI FAILURE IN 25,900 HRS



[Mainstage]



# LOCKUP PROBABILITY ASSESSMENT ELECTRICAL LOCKUP

Downey source (Byron Andrews)

1st FAILURE		2nd/3rd FAILURE		ENGINE MTBF	VEHICLE MTBF
NO	CAUSE	MTBF	CAUSE		
MODES UNAFFECTED BY SOFTWARE CHANGE, COMBINED 1 IN 827,000					
1	LOSS OF 1 OF 3 VEHICLE POWER BUSES	7692	LOSS OF 1 OF 4 CROSS CHANNEL FUEL FLOW COILS	N/A	1.0M =
2	1 OF 2 CONTROLLER IE CHANNELS FAIL	90,000	1 OF 2 FUEL FLOW COILS FAIL AFTER LIFTOFF	24M $90M \times 265$	8.0M $\div 3$
3			3 OF 4 FUEL FLOW COILS FAIL AFTER LIFTOFF	N/A	12M
ADDITIONAL RISK DUE TO SOFTWARE CHANGE, COMBINED 1 IN 1,526,000					
1	LOSS OF 1 OF 4 FUEL FLOW COILS BEFORE LIFTOFF	276	LOSS OF CROSS CHANNEL VEHICLE POWER BUS	23,000 $3 \times 7692$	2.1M $\div 3$
2	1 OF 4 FUEL FLOW COILS FAIL BEFORE LIFTOFF	276	2 OF 3 FUEL FLOW COILS FAIL AFTER LIFTOFF	94,000	8.6M
3	1 OF 4 FUEL FLOW COILS FAIL BEFORE LIFTOFF	276	CROSS CHANNEL CONTROLLER IE FAILS AFTER LIFTOFF	179,000	16M

EACH BUS services two Eng's A & B

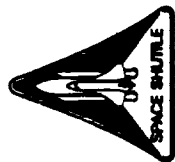
179,000  
2 either one

3x 92



TOTAL COMBINED RISK IS 1 IN 536,681

$$\frac{1}{827K} + \frac{1}{1.5M} = \frac{1}{X}$$

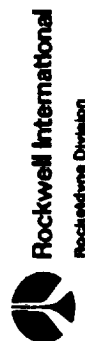


## LAUNCH COMMIT CRITERIA

---

- PRESTART FUEL FLOW CHANNEL MONITORING
  - "REPORT ONLY" FAILURE (FID) DISPLAYED IF FAILURE DETECTED
- CAUSES
  - FLOWMETER MOTION INDUCED BY TANKING OR MPS TROUBLE - SHOOTING
  - ACTION: CONTROLLER RESET TO CLEAR AND PROCEED
  - 60 MINUTES OF CONTINUOUS BLEED FLOW PRIOR TO ENGINE START
- CONTROLLER INTERNAL FLOW SENSING ELECTRONICS FAILURE

MAC\51D2  
ABORT



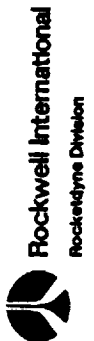


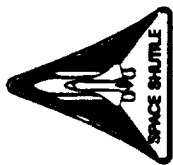
## FUEL FM LOGIC CHANGE (AA35) LAUNCH COMMIT CRITERIA IMPACT

---

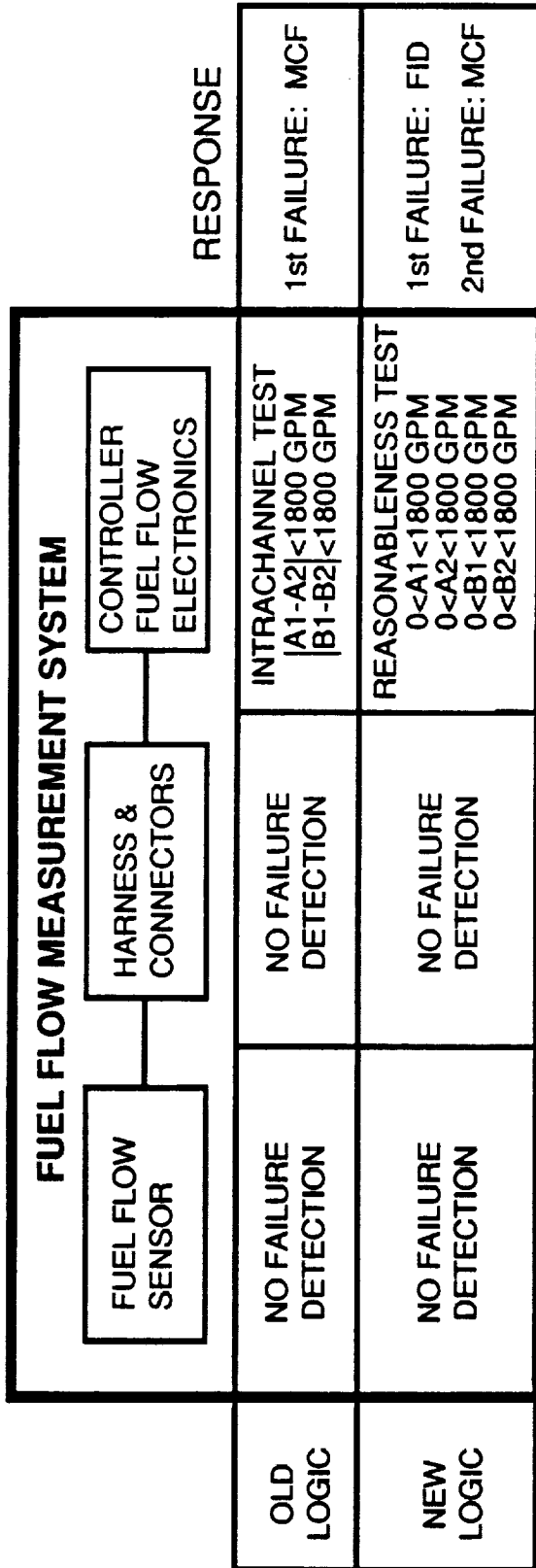
- ANALYSIS
  - EVALUATION OF SYSTEM AND FLOW SENSOR CIRCUIT INDICATE TWO POTENTIAL CONDITIONS THAT MAY RESULT IN EXCEEDANCE OF QUALIFICATION LIMIT
  - ROTATION OF FLOWMETER BLADE PASS PICKUP WILL START COUNTER AND SUBSEQUENT REVERSE ROTATION OF BLADE STOPS COUNTER RESULTING IN SINGLE DATA SPIKE
  - THIS CONDITION COULD ONLY OCCUR DURING INITIAL CHILLING OF ENGINE AND AT THE TIME RECIRC PUMP IS TURNED ON, OR MPS TROUBLE-SHOOTING THAT DISTURBS ENGINE FLOW
  - REQUIRES THREE STRIKES TO CAUSE FID
- INTERMITTENT NOISE OF THE ZERO CROSSING DETECTOR WITHIN CONTROLLER EXCEEDING LIMIT FOR THREE STRIKES
- NO OCCURRENCE IN PROGRAM HISTORY

LOC\_FUEL.PPT

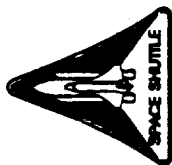




# FUEL FLOW SENSING MONITOR LOGIC PRELAUNCH LOGIC COMPARISON



PROBABILITY OF CONTROLLER FUEL FLOW ELECTRONICS FAILURE			ACTION
TIME		FLIGHT MTBF	
T-34 HOURS	TO T-5 MIN	1 IN 4,456	SCRUB IF NOT MPS RELATED
T-5 MIN	TO T-31 SEC	1 IN 1,800,000	SCRUB
T-31 SEC	TO T <sub>0</sub>	1 IN 7,200,000	NO ACTION
T <sub>0</sub>	TO MECO	1 IN 135,000	ACTIVE



## **STS-51 PAD ABORT RATIONALE FOR FLIGHT**

---

- FAILURE ISOLATED TO FLOW SENSOR PICKUP COIL
- ME-2 SENSORS REPLACED WITH MORE FAVORABLE MTBF UNITS
  - SPECIAL COIL RESISTANCE CHECK SUCCESSFULLY COMPLETED
- MODIFIED SOFTWARE IN PLACE FOR LAUNCH WITH ONE FAILED COIL
  - IMPROVES LAUNCH PROBABILITY BY FACTOR OF 700
  - SOFTWARE VERIFICATIONS & AUDITS SUCCESSFULLY COMPLETED
  - ALL HOT FIRE CERTIFICATION TESTS SUCCESSFULLY COMPLETED
- REPORT ONLY FID RESPONSE LCC REQUIREMENTS IN PLACE



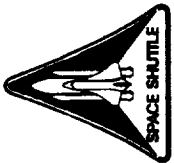
## FUEL FLOW LOGIC CHANGES FOR STS-58

---

- EVALUATE RESUMEABLE MCF RESPONSE FOR 1ST FUEL FLOW SENSOR CHANNEL FAILURE PRESTART
- MONITOR UP TO START ENABLE (START - 2.3 SEC)
- EVALUATE APPROACH & IMPLEMENT MAINSTAGE LOGIC TO OPERATE ON A SINGLE FLOW COIL
- ISSUE ELECTRICAL LOCKUP RESPONSE AFTER FOURTH FAILURE

MAC\51D2  
BU





## NEW SENSOR DESIGN

---

- INCORPORATES NEW POTTING MATERIAL LESS SUSCEPTIBLE TO THERMAL CRACKING
  - TEST SPECIMEN SCREENING PROGRAM OF 9 CANDIDATE MATERIALS
  - TWO UNITS IN TEST (07/93) FOR 5000 SEC DESIGN VALIDATION
  - PRODUCTION HARDWARE 09/94
- ACTION UNDER TAKEN WITH MSFC CONCURRENCE
  - AUTHORIZE LONG LEAD PROCUREMENT NOW
  - RETURN DELIVERED GROUP 4 UNITS TO SALVAGE CONNECTORS
  - PRODUCTION HARDWARE (4 ENGINE SETS) BY 02/94

MAC\51D2  
BU



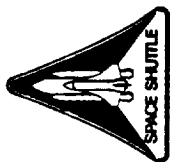
Rockwell International  
Rocketdyne Division

56

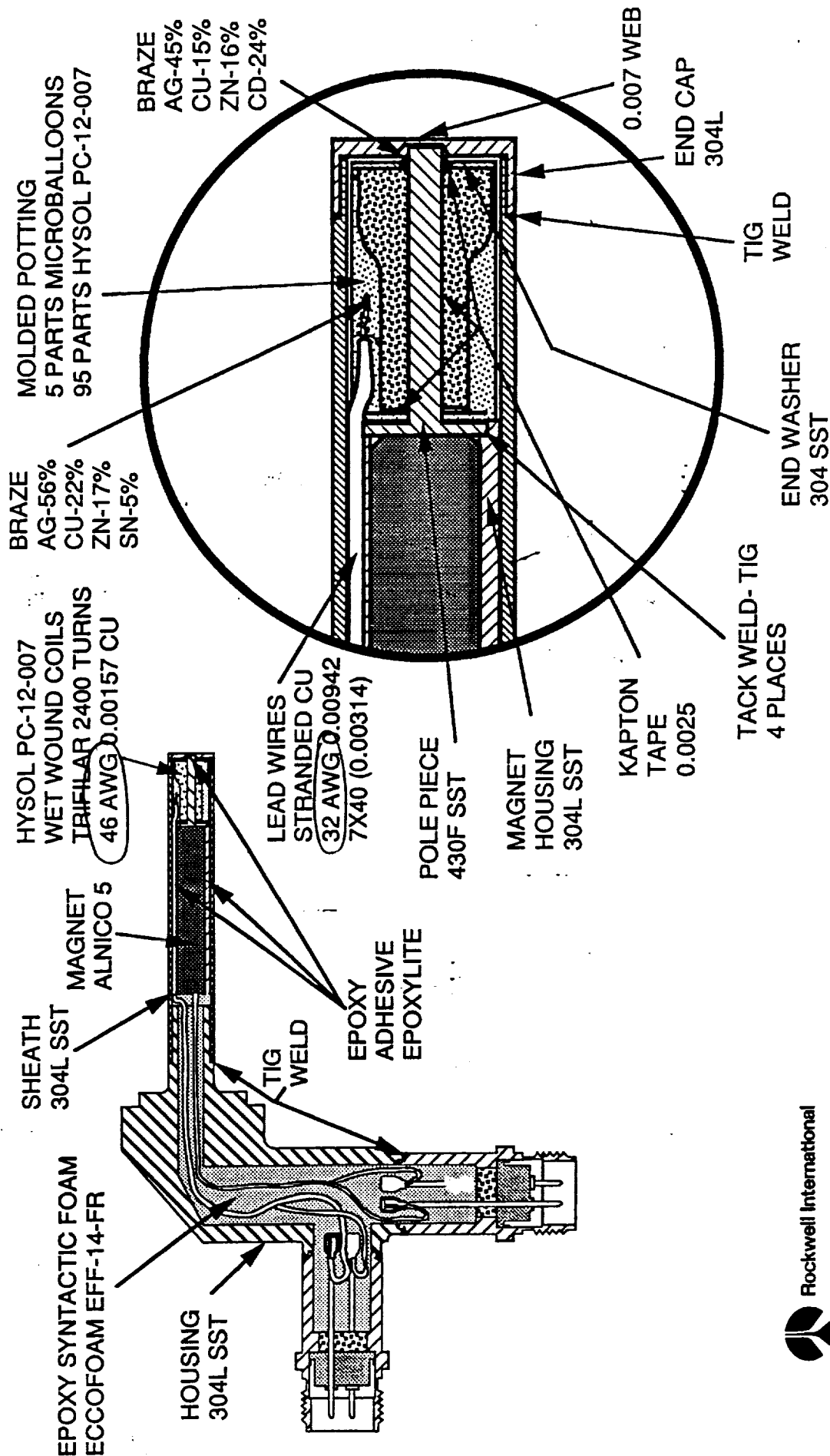


# HPFTP SPEED SENSOR

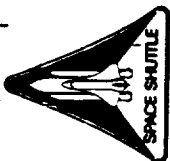
## RES7005-085 CUTAWAY (1X SCALE)



4/30/93 11:30 HRS



# PERFORMING SENSOR CHECKOUT DURING PSN-3

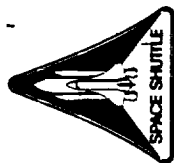


- **APPROACH**

- PERFORM CHECKOUT ON COMMAND IN PSN-3 AFTER CHILL STABILIZATION
- RESTRICT CHECKOUT TO FUEL FLOW SENSORS ONLY
- REQUIRES 10 SECONDS (APPROX.) FOR FUEL FLOW SENSORS

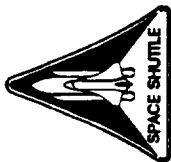
- **DISADVANTAGES**

- PUTS OUT FALSE READINGS ON ALL PRESSURE, TEMPERATURE, SPEED, FLOW AND VIBRATION SENSORS FOR DURATION OF CHECK
- TEMPORARY LOSS OF LCC MONITORING, BOTH CONTROLLER AND GROUND MONITORED, FOR SENSOR MEASUREMENTS ORIGINATING WITH THE CONTROLLER



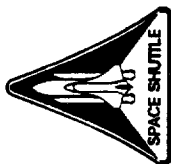
## PERFORM SENSOR CHECKOUT DURING PSN-3

- **SSME CONTROLLER CHANGES**
  - MAKE COMMAND ACCEPTABLE IN PSN-3
  - BYPASS SENSOR QUALIFICATION MONITORING AND PURGE AND ANCILLARY SYSTEMS MONITORING AS APPROPRIATE
  - BYPASS RECALIBRATION OF PRESSURE SENSORS
  - RESTRICT CHECKOUT TO FLOW SENSORS ONLY
- **REQUIRES SIGNIFICANT SOFTWARE MODIFICATIONS**
  - BOTH SSME CONTROLLER SOFTWARE AND KSC LAUNCH PROCESSING SYSTEMS AFFECTED
  - SCOPE OF THE SOFTWARE CHANGE MORE COMPLEX THAN THE PROPOSED FUEL FLOW LOGIC CHANGE
- **CONCERN**
  - LOSS OF LCC VISIBILITY FOR DURATION OF CHECK - MUST MASK GROUND SOFTWARE



# **LOCKUP PROBABILITY ASSESSMENT** **ELECTRICAL LOCKUP**

NO.	1st FAILURE		2nd/3rd FAILURE		ENGINE MTBF	VEHICLE MTBF
	CAUSE	MTBF	CAUSE	MTBF		
1	1 OF 2 MCC PC SENSORS FAILS	961	1 OF 2 CROSS CHANNEL MCC PC SENSORS FAIL	961	900,000	300,000
2	LOSS OF 1 OF 3 VEHICLE POWER BUSES	7692	LOSS OF 1 OF 4 CROSS CHANNEL FUEL FLOW COILS	132	N/A	1.0M
3	LOSS OF 1 OF 12 FUEL FLOW COILS BEFORE LIFTOFF	92	LOSS OF CROSS CHANNEL VEHICLE POWER BUS	23,000	N/A	2.1M
4	1 OF 2 CONTROLLER IE CHANNELS FAIL	90,000	1 OF 2 FUEL FLOW COILS FAIL AFTER LIFTOFF	265	24M	8.0M
5	1 OF 4 FUEL FLOW COILS FAIL BEFORE LIFTOFF	276	2 OF 3 FUEL FLOW COILS FAIL AFTER LIFTOFF	94,000	26M	8.6M
6			3 OF 4 FUEL FLOW COILS FAIL AFTER LIFTOFF	N/A	37M	12M
7	1 OF 4 FUEL FLOW COILS FAIL BEFORE LIFTOFF	276	CROSS CHANNEL CONTROLLER IE FAILS AFTER LIFTOFF	179,000	49M	16M



# **LOCKUP PROBABILITY ASSESSMENT** **HYDRAULIC LOCKUP**

NO.	1st FAILURE		2nd/3rd FAILURE		ENGINE MTBF	VEHICLE MTBF
	CAUSE	MTBF	CAUSE	MTBF		
1	APU FAILURE AFTER LIFTOFF		NOT REQUIRED			345
2	1 OF 5 ACTUATORS FAIL AFTER LIFTOFF	4,000	1 OF 5 CROSS CHANNEL ACTUATORS FAIL	4,000	16M	5.3M
3	LOSS OF ONE VEHICLE POWER BUS	7692	1 OF 10 CROSS CHANNEL ACTUATORS FAIL	2,000	N/A	15M
4	1 OF 10 ACTUATORS FAIL AFTER LIFTOFF	2,000	CROSS CHANNEL CONTROLLER OE FAILS	179,000	358M	119M

## **Section 12.0**

### **Appendix**

Space Systems Division  
Honeywell Inc.  
13350 U.S. Highway 19 North  
Clearwater, Florida 34624-7290  
813 539-3273  
813 539-3347 Fax

09 September 1993

CEL-K-472-1108

Rockwell International Corporation  
Rocketdyne Division  
6633 Canoga Avenue  
Canoga Park, CA 91303

Attention: Mr. R. E. Bartley

Subject: SSMEC DEPOT P.O. R90SPA89550074  
Customer Engineering Letter - 3-SSEC-2332  
**F42 HEALTH CHECK**

Gentlemen:

Under separate cover, we have forwarded four (4) copies of the subject CEL, in response to the above reference, to Mr. R. Precourt, one (1) copy to Mr. G. Brown and one (1) copy to Data Management.

Should you have any questions, please contact the undersigned at 813-539-3273.

Yours truly,



C.E. Lee  
Contracts Specialist

CEL/mnr

cc: R.A. Precourt - PA19 (4)  
G. Brown - PA05 (4)  
Data Management - Rocketdyne - AB16 (1)  
T. McLeod - Rocketdyne Resident - 848-5 (2)(Internal)

**HONEYWELL**  
Avionics  
Clearwater, Florida

C.E.L. NUMBER 3-SSEC-2332-Rev. A  
9 September 1993  
Page 1 of 4

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Rockwell International  
Rocketdyne Division  
6633 Canoga Avenue  
Canoga Park, CA 91303

Attention: R.A. Precourt, Project Manager  
Avionics Subcontracts/PA-19

Subject: F42 Health Check

**SUMMARY:**

F42 completed all testing without incident on August 28, 1993. It was returned to Honeywell for a health check on August 25, 1993. This unit had reported a Channel A Q1A2 Flowrate failure which resulted in a launch abort. Health check included special tests specifically designed and performed to verify the isolation and integrity of the Q1A2 flow signal channel. Environmental exposure was performed with an oscilloscope monitoring the Q1A2 flow signal channel at all times; this included three thermal cycles (one cold start, two high voltage) and 69 minutes of vibration. Pre and post environmental Automatic Test Equipment System (ATES) functional tests were also performed. Worst case analysis determined that a short from an adjacent signal path would result in a maximum current six times less than the current required to fuse the Q1A2 flow sensor coil. Health check revealed no deficiencies in the performance of F42. Analysis revealed no viable failure scenario which warrants any concern for the integrity of F42.

**CONCLUSION:**

Since F42 experienced no failures during the STS 51 launch abort and based on the successful completion of the health check, F42 was returned to Stennis Space Center on September 2, 1993.

**ANALYSIS:**

Review of the internal controller wiring showed that the  $\pm 15V$  signal paths were the highest regulated voltage sources adjacent to the Q1A2 flow signal path. No unregulated voltage sources are in the proximity of this path. It was then determined by worst case analysis that the  $\pm 15V$  sources could supply no more than 79 mA if shorted directly to the Q1A2 flow signal path. The resulting current is six times less than the current required (500 mA) to fuse open the coil in the Q1A2 flow sensor (based on a 190  $\Omega$  coil resistance at cryogenic temperatures). At room temperatures the resulting current (12.8 mA) from a short would be thirty-nine times less than the fusing current of the Q1A2 flow sensor coil (1170  $\Omega$  at room temperature).



INVESTIGATION:

F42 was received on August 25, 1993. A visual inspection ("OK") and internal pressure check (8.5 psig) were performed. Routine cleaning of the controller and connector mating surfaces was omitted, connector savers were installed. Electrical bonding of Outboard Cover to chassis (0.06 m $\Omega$ ) and Inboard Cover to chassis (0.05 m $\Omega$ ) was verified. This completed incoming receiving inspection. No anomalies or deficiencies were observed.

A baseline pre-environmental ATES functional test was performed without incident. Flow signal channel data was reviewed and compared against data from previous ATES functional tests (see Table 1). No discernible change in the test data was noted in this comparison.

Flow signal Channel resistance was measured using a hand held Fluke as follows:

J107 A wrt B	Fuel Flowmeter	Ch A (Q1A1)	PRI	* 632 $\Omega$
J107 B wrt A	Fuel Flowmeter	Ch A (Q1A1)	PRI	* 587 $\Omega$
J107 C wrt D	Fuel Flowmeter	Ch A (Q1A2)	SEC	82.38 k $\Omega$
J107 D wrt C	Fuel Flowmeter	Ch A (Q1A2)	SEC	69.68 k $\Omega$
J108 a wrt b	Fuel Flowmeter	Ch B (Q1B1)	PRI	82.25 k $\Omega$
J108 b wrt a	Fuel Flowmeter	Ch B (Q1B1)	PRI	69.68 k $\Omega$
J108 W wrt j	Fuel Flowmeter	Ch B (Q1B2)	SEC	* 592 $\Omega$
J108 j wrt W	Fuel Flowmeter	Ch B (Q1B2)	SEC	* 633 $\Omega$

(\*500 Hz FET Switch, DG184 IE3)

A flight-type flow sensor (P/N 148AL, S/N 545) was connected as follows to perform fault insertion test and thermal cycle testing of the Q1A1 and Q1A2 flow signal channels.

<u>Sensor</u>	<u>Controller</u>
Pin 1	J107 A
Pin 2	J107 B
Pin 3	J107 C
Pin 4	J107 D

FAULT INSERTION:

Short	J107 A	to	J107 B	While running in Group 1 Sensor mode
Short	J107 C	to	J107 D	While running in Group 1 Sensor mode
Short	J107 A	to	J107 B	While running in Normal Sensor mode
Short	J107 C	to	J107 D	While running in Normal Sensor mode
Open	J107	at	A	While running in Group 1 Sensor mode
Open	J107	at	B	While running in Group 1 Sensor mode
Open	J107	at	C	While running in Group 1 Sensor mode
Open	J107	at	D	While running in Group 1 Sensor mode
Open	J107	at	A	While running in Normal Sensor mode
Open	J107	at	B	While running in Normal Sensor mode
Open	J107	at	C	While running in Normal Sensor mode
Open	J107	at	D	While running in Normal Sensor mode

Controller responses to the above fault insertion test were correct and as expected.

The flight-type flow sensor was removed to perform a manual input filter test for Q1A2. This manual test verified the low pass filter has a roll-off frequency of  $127 \pm 32\text{Hz}$ . In addition, data from the ATES functional test of 11 June 1992 was compared with the pre/post environment ATES functional test. Results are below:

	<u>6/11/92(ATES #1)</u>	<u>8/26/93 (ATES #2)</u>	<u>8/28/93 (ATES #2)</u>
Q1A1 filter Roll-off	131 Hz	120 Hz	122 Hz
Q1A2 filter Roll-off	127 Hz	122 Hz	126 Hz

With the flight-type flow sensor re-connected to F42 the thermal chamber was ramped to -45°C. All temperature ramps were performed in the Group 1 Sensor (GR1S) checkout mode. This allowed virtually uninterrupted monitoring of the 500 Hz test signal (J107 A wrt B, J107 C wrt D) with the digital oscilloscope set to trigger on any changes. No voltages were seen to have been generated by the controller on the Q1A1 or Q1A2 inputs on the flight type flow sensor. F42 was powered-off for a four hour cold dwell. A cold start was then initiated and the Controller completed the first thermal cycle without incident. This concluded testing with the flight-type sensor.

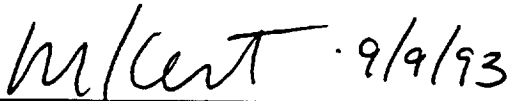
All three axes of vibration were performed with a profile of 10 minutes at -3dB (GR1S), 3 minutes at 0dB (Environmental Command Sequence(ECS)) and 10 minutes at -3dB (7 minutes in GR1S, 3 minutes in ECS). The 500 Hz was again continuously monitored at the Controller checkout console (CCC) test point panel (J107 A wrt B, J107 C wrt D). F42 completed the 69 minutes of vibration without incident. (Note: The 0dB vibration level is the normal controller acceptance test level vibration environment.)

F42 was returned to thermal chamber and successfully completed the second (high voltage) and third (high voltage) cycles with the Oscilloscope monitoring the CCC test point panel as before. The GR1S mode was again commanded during all temperature ramps to provide additional exposure to any flow signal channel failure mode. No anomalies of the 500 Hz were detected by the oscilloscope.

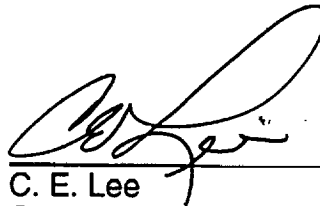
A post environmental ATES run was completed on 28 August 1993. Flow-signal channel data was compared with a previous ATES run on 11 June 1992 (see Table I). No significant shifts were observed.

In summary, F42 passed all phases of health check. Worst case analysis and special testing with the flight-type sensors verified the integrity and isolation of the Q1A2 flow signal channel. F42 was shipped to Stennis Space Center on 2 September 1993.

Prepared by N. Bier

 9/9/93

M. Kert  
Program Manager  
Space Shuttle Main Engine Controller



C. E. Lee  
Contracts Specialist  
Space Shuttle Main Engine Controller

TABLE I  
F42 ATES Flow Channel Data

**MODULE 514 - IE Flow Signal Channel Test**

	11-Jun-92	26-Aug-93	28-Aug-93	LOW LIMIT	HIGH LIMIT
12Hz/.15V Q1A1	6c83	6c84	6c82	6ab5	6e17
12Hz/.15V Q1B1	6c7e	6c83	6c7d	6ab5	6e17
12Hz/.15V Q1A2	6c85	6c88	6c83	6ab5	6e17
12Hz/.15V Q1B2	6c7b	6c84	6c7e	6ab5	6e17
340Hz/13V Q1A1	03d4	03d5	03d4	03d2	03d6
340Hz/13V Q1B1	03d4	03d5	03d4	03d2	03d6
340Hz/13V Q1A2	03d4	03d4	03d4	03d2	03d6
340Hz/13V Q1B2	03d5	03d4	03d4	03d2	03d6
4Hz/1V Q1A1	ffff	0000	0000	0000	ffff
4Hz/1V Q1B1	0000	0000	ffff	0000	ffff
4Hz/1V Q1A2	0000	ffff	0000	0000	ffff
4Hz/1V Q1B2	ffff	0000	0000	0000	ffff

**MODULE 515 - IE Flow Input Independance Test at 12 Hz**

	11-Jun-92	26-Aug-93	28-Aug-93	LOW LIMIT	HIGH LIMIT
Q1A1 with Q1B1	029B	029A	029B	0292	02A2
Q1A1 with Q1A2	029B	029A	029B	0292	02A2
Q1A1 with Q1B2	029B	029B	029A	0292	02A2
Q1B1 with Q1A1	029A	029A	029B	0292	02A2
Q1B1 with Q1A2	029A	029A	029A	0292	02A2
Q1B1 with Q1B2	029A	029A	029A	0292	02A2
Q1A2 with Q1A1	029A	029B	029B	0292	02A2
Q1A2 with Q1B1	029B	029A	029B	0292	02A2
Q1A2 with Q1B2	029B	029A	029A	0292	02A2
Q1B2 with Q1A1	029A	029A	029B	0292	02A2
Q1B2 with Q1A2	029B	029B	029A	0292	02A2
Q1B2 with Q1B1	029B	029B	029B	0292	02A2

# Internal Letter



Rockwell International

Date: . 30-August-1993

No: . 93-PS-107-112

TO: (Name, Organization, Internal Address)

- . G.H. Skopp & J.L. Pennock
- . Depts. 709 & 477
- . Canoga-Rocketdyne

FROM: (Name, Organization, Internal Address, Phone)

- . P. J. Brzeski
- . Dept. 107 - AC58
- . Canoga-Rocketdyne
- . 586-6642

Subject: . **STS-51 Abort Team Action Item #30**

The STS-51 abort on 12 August 1993 was caused when the channel A fuel flow sensor on Engine 2033 failed the fuel flow intra-channel (A versus B) qualification limit check. During the initial investigation it was wrongly assumed that fuel flow sensor #1 as listed in the ACTS database was the channel A sensor. Paperwork listing the serial number of the #1 sensor as the failed unit was prepared in order to expedite the failure analysis. When the channel A sensor arrived at the vendor (Rosemount) the wrong serial number was on the Rocketdyne paperwork. In actuality the #1 sensor is channel B and the #2 sensor is channel A. The #3 sensor is not used during flight but is installed on the engine.

The three fuel flow sensors are currently listed in the ACTS database as follows:

- Fuel flow pickup #1 (LRU code J601)
- Fuel flow pickup #2 (LRU code J602)
- Fuel flow pickup #3 (LRU code J603)

It is requested that the part names be changed in the ACTS database to more accurately reflect the sensor channel positions as called out in the Main Engine Controller logic. The LRU codes will not change.

- from: Fuel flow pickup #1 to: Fuel flow sensor CH B
- from: Fuel flow pickup #2 to: Fuel flow sensor CH A
- from: Fuel flow pickup #3 to: Fuel flow sensor NFD

Even though the MCC Pc sensors #1 and #2 are channels A and B, respectively, in order to maintain consistency the part names should be changed as follows:

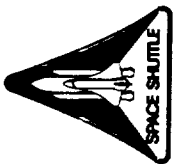
- from: Main chamber press sensor #1 to: Main chamber press sensor CH A
- from: Main chamber press sensor #2 to: Main chamber press sensor CH B

As with the fuel flow sensors, the LRU codes will not change. The channel A sensor LRUs are J201 or J231 and the channel B sensor LRUs are J202 or J232.

Paul Brzeski  
SSME Flight Support Team

cc:

- J. Rivetti (AB08)
- A. Hill (PA07)
- G. Gilmartin (AB32)
- P. Seitz (AC58)
- B. Wood (AC04)
- K. Kan (AC58)
- D. Hausman (AC58)
- STS-51 Abort Team Files (AC58)



# STS-51 ABORT TEAM

## ACTION ITEM #30

### ● PROBLEM

- THE TITLES OF THE 3 FUEL FLOW SENSORS IN THE ACTS MAINFRAME DATABASE ARE BY NUMBER NOT CHANNEL

- FUEL FLOW PICKUP #1 (LRU CODE J601)
- FUEL FLOW PICKUP #2 (LRU CODE J602)
- FUEL FLOW PICKUP #3 (LRU CODE J603)

- STS-51 ABORT CAUSED BY SENSOR CHANNEL A FAILURE

- CONFUSION AROSE OVER WHICH SENSOR ACTUALLY FAILED BECAUSE IT WAS WRONGLY ASSUMED CHANNEL A WAS SENSOR #1

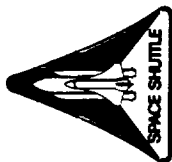
### ● ACTUAL CONFIGURATION:

- |             |             |           |                |
|-------------|-------------|-----------|----------------|
| ● PICKUP #1 | CHANNEL B   | TAP KF1CF | CONNECTOR P156 |
| ● PICKUP #2 | CHANNEL A   | TAP KF1BF | CONNECTOR P147 |
| ● PICKUP #3 | CHANNEL NFD | TAP KF1AF |                |



Rockwell International  
Rockeidyne Division

51 ITEM.WRP



# STS-51 ABORT TEAM

## ACTION ITEM #30

### ● SOLUTION

- CHANGE ACTS PART NAMES TO REFLECT SENSOR CHANNEL POSITIONS AS CALLED OUT IN CONTROLLER LOGIC

#### ● FROM:

- FUEL FLOW PICKUP #1
- FUEL FLOW PICKUP #2
- FUEL FLOW PICKUP #3

#### ● TO:

- FUEL FLOW SENSOR CH B
- FUEL FLOW SENSOR CH A
- FUEL FLOW SENSOR NFD

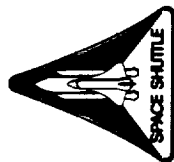
- LRU NUMBERS WILL NOT CHANGE

- HPFTP TURBINE DISCHARGE TEMP SENSORS HAD SIMILAR PROBLEM

- SENSOR #1 IS CHANNEL B (LRU CODE J301)
- SENSOR #2 IS CHANNEL A (LRU CODE J302)

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# STS-51 ABORT TEAM

## ACTION ITEM #30

### ● IMPLEMENTATION

- ENGINEERING FUNCTIONS HAVE RESPONSIBILITY FOR ACCURACY OF THEIR DATA/INFORMATION IN ACTS DATABASE
- SUBMIT INTERNAL LETTER TO RESPONSIBLE MANAGERS/ENGINEERS
  - GIL SKOPP (FLIGHT)
  - JOHN PENNOCK (DEVELOPMENT)
  - JOE RIVETTI (QUALITY)
- ALSO CHANGE MCC Pc SENSORS (EVEN THOUGH #1 IS CH A)
  - FROM:
    - MAIN CHAMBER PRESS SENSOR #1 (LRUs J201 or J231)
    - MAIN CHAMBER PRESS SENSOR #2 (LRUs J202 or J232)
  - TO:
    - MAIN CHAMBER PRESS SENSOR CH A (LRUs J201 or J231)
    - MAIN CHAMBER PRESS SENSOR CH B (LRUs J202 or J232)

51 ITEM.WRD